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Prediction of Mineral Quality of Irrigation Return Flow. Volume V. Detailed Return Flow Salinity and Nutrient Simulation Model

Bureau of Reclamation, Denver, Colo. Engineering & Research Ctr.

Prepared for

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The development and evaluation of modeling capability to simulate and predict the effects of irrigation on the quality of return flows are documented in the five volumes of this report. The report contains two different modeling packages which represent different levels of detail and sophistication. Volumes I, II, and IV pertain to the model package given in Volume III. Volume V contains the more sophisticated model. User's manuals are included in Volumes III and V.

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PREDICTION OF MINERAL QUALITY OF IRRIGATION RETURN FLOW

VOLUME V

DETAILED RETURN FLOW SALINITY AND NUTRIENT SIMULATION MODEL

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to the knowledge essential if the EPA is to meet the requirements of environmental laws that it establish and enforce pollution control standards which are reasonable, cost effective and provide adequate protection for the American public.

William C Galegar

William C. Galegar
Director
Robert S. Kerr Environmental
Research Laboratory

PREFACE

This report is one of a set which documents the development and verification of a digital computer modeling effort to predict the mineral quality changes in return flows occurring as a result of irrigating agricultural lands. The set consists of five separate volumes under one general title as follows:

"Prediction of Mineral Quality of Irrigation Return Flow"

Volume I.	Summary Report and Verification
Volume II.	Vernal Field Study
Volume III.	Simulation Model of Conjunctive Use and Water Quality for a River Basin System
Volume IV.	Data Analysis Utility Programs
Volume V.	Detailed Return Flow Salinity and Nutrient Simulation Model

This set of reports represents the culmination of an effort started in May 1969 by an interagency agreement between the U.S. Bureau of Reclamation and the Federal Water Pollution Control Administration on a joint research proposal on the "Prediction of Mineral Quality of Return Flow Water from Irrigated Land." This research project has had three different project identification numbers during the project period. These numbers (13030 EII, EPA-IAG-048-(D), and EPA-IAG-D4-0371) are given to avoid confusion on the part of individuals who have previously tried to acquire project reports for the earlier project numbers.

ABSTRACT

A return flow quality simulation model is described which models the plant-soil-aquifer system from the soil surface to a tile or open drain. Processes simulated include evapotranspiration, unsaturated and saturated water flow, solution-precipitation of slightly soluble salts, ion exchange, ion pairing, nitrogen transformations, crop uptake of nitrogen, and the movement and redistribution of salts and nutrients.

The dynamic non-steady-state model predicts the concentrations of calcium, magnesium, sodium, ammonium, bicarbonate, carbonate, chloride, sulfate, NO_3-N, and Urea-N contained in soil, aquifer, and drain waters. Concentrations of organic-N; exchangeable calcium, magnesium, sodium, and ammonium; and gypsum are predicted within the soil and aquifer materials.

Users' manuals for each basic subprogram are included, and a sample problem illustrates the use of the model. Model output can serve as input to the conjunctive use model described in Volume III; serve as input to other models on a nodal or point source basis; or stand alone depending on the type and scope of the particular study.

This report was submitted in fulfillment of project EPA-IAG-D4-0371 by the U.S. Bureau of Reclamation, Engineering and Research Center, under the partial sponsorship of the Environmental Protection Agency. Work was completed as of June 15, 1975.

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Messrs. Norman A. Roth, Roger W. Falkenstein, and Gary C. Shulstad of the Missouri-Souris Projects Office developed the basic input data used in the sample model runs contained in the Appendix.

The major sponsorship of this work was provided by the Mid-Pacific Region and Water Quality Office of the U.S. Bureau of Reclamation.

SECTION I

CONCLUSIONS

The simulation model described in this volume is a highly flexible, sophisticated tool which can be used to predict the effects of initial soil and aquifer conditions, cultural practices, input water quality, and other factors on water and soil chemistries throughout the plant-soil-aquifer system. Output can be used as input to other models which consider the combined effects of several point sources on stream quality in a river basin or subbasin.

The model also has many stand-alone applications such as predictions involving the reclamation of saline and sodic soils, drain spacing design, salt and nutrient pollution studies on soils and aquifers, consumptive use predictions, and irrigation scheduling.

Potential model applications (those which would require additional programing or modifications) include prediction of crop response to salinity, optimization of nitrogen fertilization schedules, irrigation scheduling (including unsaturated flow and salinity), and prediction of additional quality parameters such as pesticides, phosphates, and trace elements.

The flexibility built into the model allows the user to select the degree of modeling sophistication needed for a particular application. This can range from rough approximations to complete usage of the model's capabilities.

SECTION II

RECOMMENDATIONS

1. The total simulation capabilities of this model should be utilized only when a maximal effort is indicated by the data and type of application. For reconnaissance and survey applications, numerous submodel bypass options are available to the user.

2. Although the primary outputs from the model are flow and quality predictions associated with a tile or open drain, other model applications involving predictions within the plant-soil-aquifer system are extremely useful.

3. This model (Volume V) should be interfaced with the conjunctive use model (Volume III) when flow and quality predictions are wanted for a river basin or subbasin (e.g. more than one node), when more flow and chemistry detail is wanted in the unsaturated and saturated zones, or when predictions of nitrogen transformations are desired.

4. Additional research is needed to develop and refine methodology to select the input data used in this and other simulation models.

5. Additional field verification must be undertaken on this and other models before they can be applied with a high degree of confidence. The current confidence level of this model can be rated as moderate with the accuracy of field predictions (areas on the order of thousands of acres) appearing to be within about 10 to 15 percent of observed data. Future verification studies could raise or lower this figure.

6. The user should read and thoroughly understand the basic methodology associated with the model before applying it.

7. An important application of this model should be its use as a basis to develop more sophisticated simulation tools.

8. Although this model can (and has) been converted to other computer systems, consideration should be given to utilization of the Bureau of Reclamation CYBER 74-28 system via remote terminals.

9. This model represents a "first generation" attempt at modeling the plant-soil-aquifer system. A "second generation" model can and should be developed at an early date. The following features should be incorporated into this more advanced modeling tool:

   a. Unsaturated and saturated flow in three dimensions.

   b. Multiple soil horizons in the flow submodels.

c. A moving water table in the unsaturated flow submodel.

d. An improved inorganic chemistry submodel which incorporates additional ion pairs and solid phases under certain conditions.

e. An improved denitrification submodel.

f. An improved plant uptake of nitrogen submodel including a variable root distribution and improved uptake functions.

g. Additional submodeling to allow simulation of acid soil chemical reactions.

h. Temperature effects in the inorganic chemistry submodel.

i. Generalization of certain reaction rate equations in nitrogen transformation submodel.

j. Addition of submodels which simulate phosphorous, pesticide, and trace element reactions and movement in soils.

k. Direct modeling of mechanical dispersion.

l. Fertilizer scheduling capability.

m. A submodel simulating crop response to salinity.

SECTION III

THE MODEL

INTRODUCTION

During the past several years there has been a growing awareness of the environmental problems created by man's present and past activities. Prominent are those concerning water quality. Whenever water is withdrawn from a natural supply and used or consumed, its characteristics are changed. In particular, irrigation water usually experiences significant alterations in passing through the soil system before it is returned to the surface, either through natural or artificial drainage pathways.

The nature of these alterations depends on many interrelated characteristics of the soil-water system. Included are physical properties governing percolation of water through a porous media and chemical characteristics which determine the nature of the chemical pathways. Both are essentially beyond man's control. In contrast, the design of artificial drainage systems, selection of crop types, and fertilization and irrigation practices are largely within man's control.

Viewed as a whole, the soil-water system is quite complex. In order to understand the processes involved, workers have traditionally dissected the system for closer inspection. Thus, the agronomist is mainly concerned with crop productivity and factors affecting it and is only indirectly concerned with movement of water beyond the root zone. In contrast, the drainage engineer is primarily concerned with estimates of deep percolation and the need to keep the water table below the root zone. In reality, activities in both saturated and unsaturated zones are related. Changes in cultural and irrigation practices affect the entire system to some degree, although transformations in time and space may mask the cause-effect relationship. However, in order to evaluate these relationships, it is essential that the individual components again be interfaced and integrated.

When new or former dryland farms are brought under irrigation, it is desirable to forecast the quality of the return flows. If similar areas have already been developed, their performance can be used to make this estimate. Where this is not possible, extrapolation from dissimilar areas can lead to gross errors. As an alternative, a simulation model of the soil-water system, based on the essential physical processes in it, can aid in predicting return flow quality.

The estimated results from a simulation of the system should not be considered or represented as exact. There are three major sources of uncertainty:

a. Model approximations and assumptions. These are made to simplify the model. They may be dictated by a lack of basic knowledge, by a lack of required data, or by the accuracy of the results required.

b. Field variability. The parameters of a natural system may possess significant spatial and temporal variations. Costs of data collections generally prevent acquisition of sufficient information to define it completely. Subjective estimates and intuitive judgment are often employed to keep costs down.

c. Stochastic processes. For example, rainfall, solar radiation, and temperature processes, are not completely understood and apparently include random components. These affect plant evapotranspiration and growth processes, as well as other portions of the system.

Despite these uncertainties, a simulation model can be used to make the most of the available data. It becomes another tool available to the decisionmaker in assessing the impact of an irrigation project.

The detailed return flow quality simulation model described in this volume was developed over a period of about 7 years and has had several contributors (see acknowledgements). The model simulates chemical and physical processes associated with agricultural lands drained by subsurface tile drainage systems. The simulation begins with field applications of water, salts, and nutrients (nitrogen) and ends with predictions of flow and water quality from the drains. In addition, the model can be applied to areas with surface drainage systems and can provide predictions of quality and flow parameters at various additional points within the plant-soil-aquifer system. The background, theory and development of the various subprograms within the model have been published elsewhere and need not be repeated here.

Numerous references are included in the brief descriptions of each subprogram. The reader is advised to thoroughly familiarize himself with these materials before attempting to utilize the model.

Detailed user's manuals and a sample problem have been included to facilitate application of the model.

MODEL DESCRIPTION - GENERAL

Consider a typical vertical section through a drainage field as shown in Figure 1. Water is applied at the land surface, either as irrigation or precipitation. A portion evaporates or becomes surface runoff. The remainder infiltrates the soil system and becomes available for use by the plants or crops. In addition to evapotranspiration, there is nitrogen uptake by the plants. As water percolates vertically to the water table, chemical reactions occur. Upon reaching the water table, flow takes place under saturated conditions, eventually reaching the drains. Chemistry changes continue to occur in this saturated system.

This brief description leads to the schematic representation of the water quality model as shown in Figure 2. Each program part or block is identified with a major component of the physical system. The conceptual model was translated to mathematical notation and programed in Fortran IV for solution by a large, third-generation computer. All programs are operational on the Control Data Corporation CYBER 74-28 computer located at the USBR Engineering and Research Center in Denver, Colorado. A brief description of each block follows.

MODEL DESCRIPTION - IRRIGATION SCHEDULING

The timing and amounts of irrigation are required for input to the Unsaturated Flow Program. Deep percolation volumes are needed by the Drainout Program. This information may be developed subjectively based on past experience, by consideration of cultural practices in similar areas, or by using manual or automatic irrigation scheduling techniques. The latter is desirable where rainfall contributes significantly in meeting plant requirements.

The philosophy involved in irrigation scheduling is to keep a daily account of soil moisture in the root zone of the crop. This is accomplished by considering major inputs (irrigation and precipitation) and withdrawals (crop evapotranspiration and deep percolation). At present, a separate program is used. Since the simple bookkeeping procedures used in this program require estimates of deep percolation losses and ignore possible contributions of water to the root zone by capillary flow, it is anticipated that the scheduling techniques will be incorporated in the Unsaturated Flow Program. This will avoid duplication of elements common to both programs, avoid incompatibilities, and speed the scheduling process.

Crop evapotranspiration is computed using the Jensen-Haise method (7, 8). Evapotranspiration is increased for 3 days following a rainfall or irrigation based on a procedure used by Jensen (8, p. 956). This curve relates evapotranspiration at various growth stages to

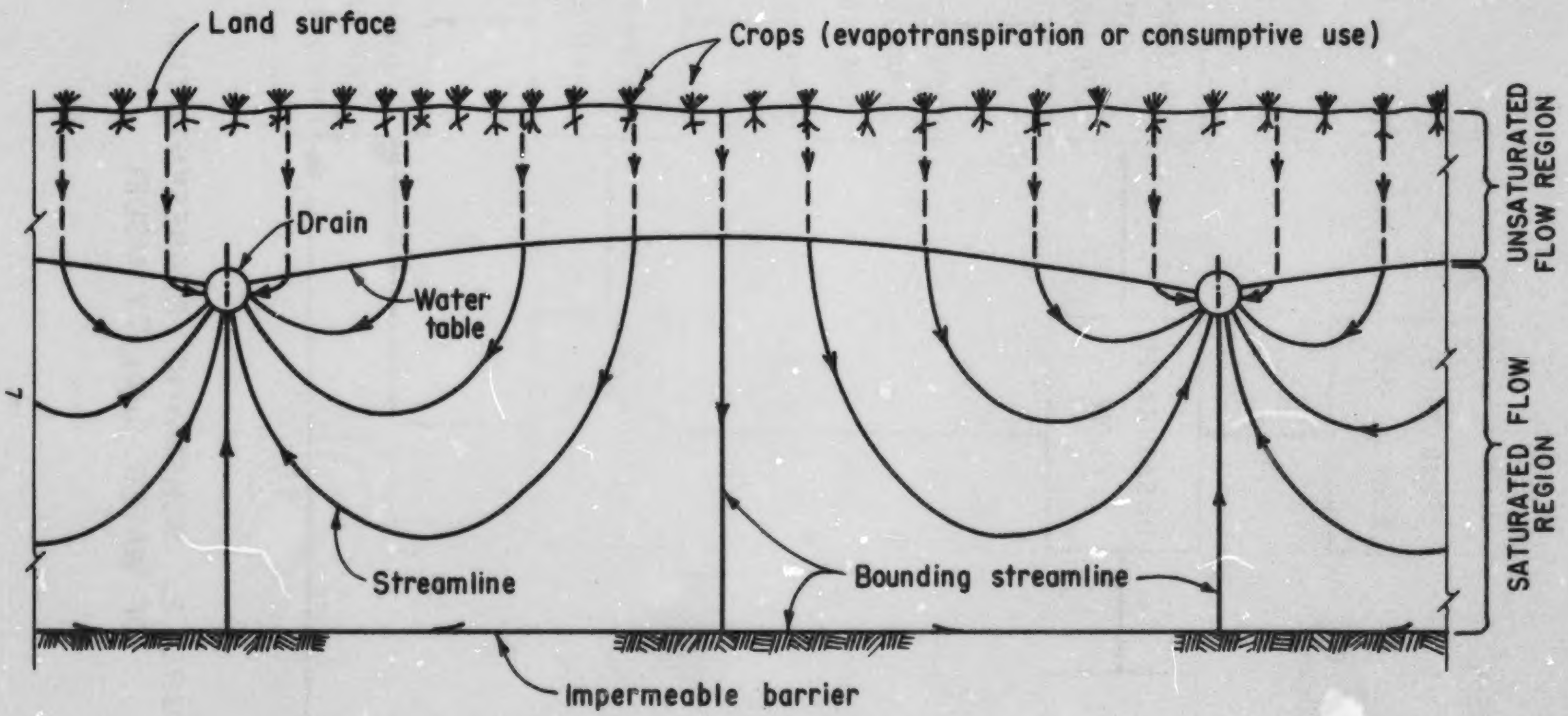
Land surface
Crops (evapotranspiration or consumptive use)
Drain
Water table
Streamline
Bounding streamline
Impermeable barrier
UNSATURATED FLOW REGION
SATURATED FLOW REGION

FIGURE 1. TYPICAL VERTICAL SECTION THROUGH DRAINAGE FIELD

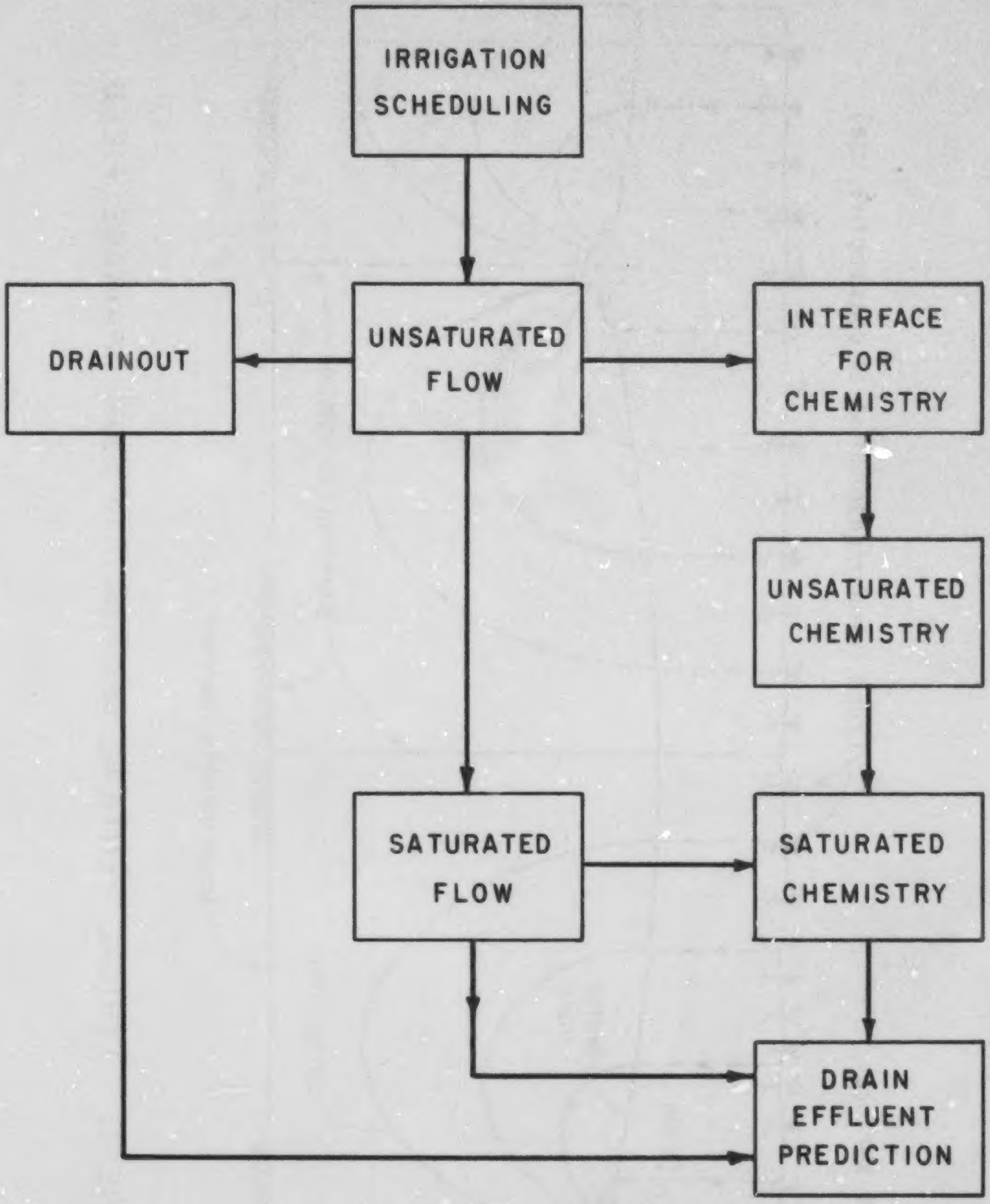
IRRIGATION SCHEDULING
DRAINOUT
UNSATURATED FLOW
INTERFACE FOR CHEMISTRY
UNSATURATED CHEMISTRY
SATURATED FLOW
SATURATED CHEMISTRY
DRAIN EFFLUENT PREDICTION

FIGURE 2. SCHEMATIC REPRESENTATION OF WATER QUALITY MODEL

the estimated potential evapotranspiration. If soil moisture is depleted below the allowable depletion percentage, evapotranspiration is reduced linearly, going to zero when all soil moisture is used.

In addition to irrigation scheduling information, average evapotranspiration rates on a semimonthly basis are computed for input to the Unsaturated Flow Program. Rainfall also is accumulated on a semimonthly basis and applied on the 15th and last day of the month.

MODEL DESCRIPTION - UNSATURATED FLOW

The unsaturated flow submodel describes the infiltration, redistribution drainage, and plant root extraction of soil moisture by a growing crop (5, pp. 8-21). Darcy's Law is assumed to apply in relating velocities to total hydraulic heads. Two modifications are made:

a. The permeability (hydraulic conductivity) is taken as a function of moisture content. This accounts for the reduced area available for flow at lower moisture contents.

b. The pressure (tension) head is taken as a function of moisture content. This accounts for the fact that different forces predominate at different moisture levels. Thus at high levels gravity is most important while at low levels capillary or molecular forces have greatest effect.

Hysteresis in both the tension head and conductivity functions is ignored. Multiphase flow (simultaneous movement of air, water vapor, and water) is not treated. Flow is assumed to be independent of quality, although the chemical processes depend on the flow.

Since both the conductivity and head are highly nonlinear with moisture content, solution of the flow equation is accomplished using numerical methods. An implicit finite difference scheme is employed and flow is treated as one dimensional in the vertical direction.

Water applications are applied on the proper date and represent "effective" values. Thus, surface runoff and evaporation from depression storage are subtracted from the total amounts. Withdrawal of water by the plants is accomplished on a macroscopic basis using a "sink" term in the governing flow equation. Thus, water is extracted continuously from the land surface to the bottom of the root zone in proportion to the root distribution. Details of flow to individual roots are not considered. Plant evapotranspiration is estimated by the Jensen-Haise method utilized in the Irrigation Scheduling Program or by using the Blaney-Criddle method. At present, root distributions are taken as constant with time and are chosen to reflect the mature growth stage.

Water to meet the specified evapotranspiration is removed node by node as long as moisture levels are above a specific lower limit, usually taken as the wilting point. If levels fall below this limit at a node no water will be withdrawn from that node and the evapotranspiration is reduced. The reduction is accumulated and listed as the "deficit moisture." No consideration is made for effects due to permanent wilting. When water contents again go above the wilting point, the plants use water at the specified evapotranspiration rates. Effects of salinity on evapotranspiration are also ignored.

The lower boundary of the one-dimensional column is taken as the water table, which for purposes of the Unsaturated Flow Program is taken as the mean annual location of the water table. Hydraulically it is treated as a zero pressure surface maintained at the saturation moisture content. The upper boundary is treated as a specified head boundary when water stands on the surface after an irrigation and as a zero flow boundary when all water from a surface application has infiltrated.

Moisture contents and water movements are then used as inputs, via the interface program, to the Unsaturated Chemistry Program. Water crossing the lower or water table boundary also acts as input to the Drainout and Saturated Flow Programs.

MODEL DESCRIPTION - DRAINOUT

The quantity of water crossing the water table during a given day, as computed by the Unsaturated Flow Program, is used to calculate the position of the water table and the drain discharge as a function of time. Standard Bureau methods for drainage system design are used. These are described by Dumm (1,2,3).

Basically, the water table shape is chosen as a fourth-degree parabola. Daily increments of flow across the water table are used in conjunction with the specific yield to compute instantaneous rises (if water moves from the unsaturated to saturated system) or instantaneous declines (if water moves from the saturated to unsaturated system by capillary flow). Equations describing the flow of water through the saturated system to parallel circular drains are then used to compute drain discharge and the fall of the water table due to drainout during the day.

Since the formulations are based on the Dupuit-Forchheimer assumptions which treat flow as parallel and neglect the effects of convergence, corrections for the depth of flow are made. Hooghoudt's equivalent depth is employed for this purpose. Approximate equations developed by Moody(11) are used to simplify the program.

Discharge values, computed on a daily basis, are accumulated to yield monthly and yearly values. By considering initial and final water table positions for each year, changes in storage during the year may be computed. Since the amount of water crossing the water table is known, application of a mass balance equation permits a semi-independent determination of the annual drain discharge. If this differs significantly from that computed using the drainout method, all daily discharge values are adjusted to yield mass balance. This approach is used because the discharge formulas are based on the first few terms of an infinite series and the constants are increased for design purposes (6, Eq 54, p. 41). Since the adjustment coefficients may differ from year to year, daily discharge values may exhibit discontinuities between years.

The resultant adjusted monthly discharge values are then used as input to the combining or drain effluent programs.

MODEL DESCRIPTION - SATURATED FLOW

The total amount of deep percolation computed by the unsaturated flow program is converted to an average annual rate for input to the saturated flow program. Using the geometry of the drainage system, a steady-state potential theory solution is employed to define stream paths or lines to the drain (12, Section 2). These solutions remove the limitations imposed by the Dupuit-Forchheimer assumptions.

A number of stream tubes may be defined to represent the two-dimensional flow system. Since an average annual seepage rate is used, a mean or average stream tube system results.

Because the equations defining the potential and stream functions are in terms of infinite series involving trigonometric, hyperbolic, and exponential functions, a node system is superimposed over the drainage system. Stream functions are computed at the nodes and required values found by linear interpolation. The corresponding potentials are then computed. With streamlines located at the hydraulic center of each tube and the potentials known, Darcy's Law is employed to calculate velocities of flow between adjacent points on the streamline. Using the known distances and porosities, these velocities are converted to travel times. Integrating or summing the travel times then yields the total time required for water crossing the water table to arrive at the drains assuming piston displacement.

The water table position is also computed and the total volume of aquifer contributing to one drain is found by numerical integration. This volume is then distributed between individual tubes using the computed travel times as the basis.

The pore volumes are used for input to the saturated chemistry programs and are necessary in calculating the soil mass and associated pore volumes in the control volumes used for calculating chemical changes. Each stream tube is treated independently in the saturated chemistry program and the results combined in the drain effluent program. This combining is based on the relative travel times for piston displacement in each tube.

MODEL DESCRIPTION - INTERFACE FOR CHEMISTRY

Moisture contents and movements from the unsaturated flow program are computed at the nodes used in the finite difference equations. In contrast, the unsaturated chemistry programs use a soil segment concept in which each segment is assumed to possess homogeneous characteristics. Because the segment centers and nodes of the unsaturated system may not coincide or be identical in number, an interface program is necessary. This program computes average moisture contents in each soil segment as well as movements of water between soil segments for a given time interval.

MODEL DESCRIPTION - UNSATURATED CHEMISTRY

The Unsaturated Chemistry Program simulates a number of important biological, chemical, and physical processes (5, pp. 21-79). These include:

a. Nitrogen transformations, including the hydrolysis of urea, mineralization-immobilization of organic-N and ammonium, nitrification of ammonium, and immobilization of nitrate. Because the rates of these transformations are slow (on the order of days or weeks), a kinetic approach is used.

b. Salt or inorganic chemistry, including ion exchange, solution-precipitation of slightly soluble salts, the formation of undissociated ion pairs, and the bicarbonate buffer system. Since reaction times are rapid (on the order of seconds or minutes), chemical equilibrium conditions are assumed.

c. Unsaturated movement and redistribution of soluble constituents.

d. Crop uptake of nitrogen.

The nitrogen rate equations were developed by applying system analysis concepts to define and limit the system and to establish pertinent variables and reaction pathways. Equations based on these variables were derived using multiple-regression analysis, reaction rate theory, and statistical thermodynamics(5,13,14). Variables include ammonium, nitrate, organic-N, and urea concentrations; temperatures; carbon-nitrogen ratios; ionic strength; and soil moisture contents.

Chemical reactions included in the salt (inorganic) chemistry portion are the dissolution and precipitation of gypsum(5,16,17,21) and calcium carbonate(5,21) undissociated ion pair reactions for calcium sulfate and magnesium sulfate(5,16,17,21), calcium-magnesium ion exchange(5,17), calcium-sodium exchange(5,21), sodium-ammonium exchange(5), and pCO_2 - Ca^{++} - HCO_3^- interactions(5). Constituents presently considered in this portion of the model are nitrate, ammonium, calcium, sodium, magnesium, bicarbonate, chloride, carbonate, and sulfate.

Solutes contained in the soil water are assumed to move with the water into and/or from adjacent segments (5, p. 23). The volume of water which moves and the mean water content of each segment (cell) over a time step are inputed from the Unsaturated Flow Model via the Interface Program. Because each cell is spatially homogeneous, solutes transferred into a segment or cell are mixed with those already in the cell.* This transfer may be either in an upward or downward direction. After each mixing operation, the soil solution phase is equilibrated with the solid and exchangeable phases. Since a number of cells, usually 10 or more, are used, this numerical technique tends to simulate physical or mechanical dispersion. This type of dispersion arises from tortuosity of the flow paths whereby flow splits and branches in going around individual soil particles. Molecular diffusion resulting from molecular energy movements is ignored and is generally significant only when little or no water movement occurs.

MODEL DESCRIPTION - SATURATED CHEMISTRY

In addition to the quantity and quality of leachate water predicted by the Unsaturated Chemistry Program, the Saturated Chemistry Program accepts the stream tube volumes determined in the Saturated Flow Program as input. Each tube is treated independently and is subdivided into a number of segments of equal volume. Leachate water is accumulated until it equals the pore volume in a single segment. It is then assumed to move by piston displacement through successive segments until it reaches the drain.(4) After each displacement, the solution phase is equilibrated with the solid and exchangeable phases.

Lateral mixing between tubes and longitudinal mixing in adjacent segments is ignored. Thus, lateral dispersion and diffusion are ignored. For saturated systems this is considered realistic.

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* This technique applies only to the unsaturated zone. A different procedure is used in the saturated region.

Chemical transformations are computed after the slug of water enters each segment. They are identical to those in the salt chemistry portion of the Unsaturated Chemistry Program except that denitrification is simulated as the deep percolation water crosses into the saturated zone. Denitrification is assumed to occur at a rate which is temperature dependent but independent of substrate (i.e., NO_3) concentrations or zero order above a "saturation" level. This level has not been well defined but probably is on the order of a fraction to a few ppm NO_3-N. Below this level, the reaction rate becomes first order and decreases as the NO_3-N concentration diminishes.

Initially, the entire saturated zone is considered as homogeneous.* Laboratory analyses of soil samples in this zone are used to define initial conditions. If more than one sample is available, analyses may be averaged or a single typical analysis used.

As each slug of water enters the segment adjacent to the water table, the slug contained in the segment adjacent to the drain is considered totally displaced. The quality of water discharging from the given stream tube is now that of the water in the segment adjacent to the drain after all reactions have occurred. It remains at this quality until another slug enters the tube at the water table. Individual tubes are combined in the Drain Effluent Prediction Program.

Although the saturated system is initially homogeneous, the passage of water down individual tubes soon produces heterogeneous conditions. As each slug moves from segment to segment, its quality changes. The chemistry of the soil complex also undergoes corresponding changes. As more tubes and segments are used, the continuous two-dimensional system is more closely approximated.

MODEL DESCRIPTION - DRAIN EFFLUENT PREDICTION

The Drain Effluent Prediction Program accepts as input the quality of each slug discharging into the drain from individual tubes, the mean travel times for piston displacement, and the monthly volume of drain discharge. Travel times are used to calculate arrival times of each slug at the drain on a tube-by-tube basis. Using these times, the resultant quality of the drain effluent is obtained by combining the appropriate slugs from individual tubes. This gives a varying drain effluent quality under steady discharge. The monthly volumes are then used to convert these results to the varying discharge pattern with the corresponding monthly qualities. The accumulated salt load out of the drain and the rate of removal are also computed.

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* The program will accept a different soil analysis for each segment. However, because stream tubes curve and segments are of different lengths, a considerable effort is required to use analyses by depth. It is anticipated that future program additions will automate this task.

All results are given for individual constituents and for the total load. The total load is taken as the sum of the individual parameters and approximates the total dissolved solids. Constituents presently considered are nitrate-nitrogen, ammonia-nitrogen, calcium, sodium, magnesium, bicarbonate, chloride, carbonate, and sulfate. Output may include cathode ray tube plots, printed listings, and punched cards. Results are on a "per-acre" basis. The assumption is made that no chemical reactions occur after the mixing process in the drain.

SECTION IV

MODEL VERIFICATION

Verifications of the various subprograms within the model are included in the literature pertaining to each program. Appropriate sections describing each subprogram should be consulted for specific citations.

Verification of the model as applied to the field situation has been obtained for an irrigated area in southwestern Colorado. An area of about 2,200 acres has been irrigated for about 75 years. Soil samples from an adjacent unirrigated area were utilized to estimate the initial soil conditions. The soil analyses from two sites were weighted with depth to obtain mean soils data. These data appear in Table 1. Profile B3 represents soils closest to the associated stream (Navajo Wash) while profile B2 represents conditions farther from the stream. Selection of sampling sites was based entirely on the experience of field personnel.

Model bypass configuration No. 1 (see Section VIII, Figure 6) was selected with the Irrigation Scheduling Program bypassed. An annual average irrigation and precipitation input sequence was derived for the simulation period (Table 2). This sequence was applied to the irrigated area for the 75-year period.

A typical cross section through the irrigated area is shown in Figure 3. The diagram includes the five stream tubes used in the simulation together with mean travel times for each. Note the relatively high travel times for flow through this aquifer.

Predicted and observed values for constituent and TDS concentrations with time are given in Figure 4. Predicted and observed mean soil profile data after about 75 years of irrigation appear in Table 3. These soil profiles were selected in approximately the same relative locations as the input profiles. The agreement between prediction and observation was on the average within about 8 percent for soil water quality and about 12 percent for stream quality. More detail in the simulation such as additional soil profiles, layering with depth, unsaturated flow and chemistry, additional ion pairs, and better estimates of CO_2 partial pressure would probably improve the agreement.

There has been some difference of opinion and confusion concerning the importance of including the chemical reactions in field simulations.(23, 24) To test the significance of the chemistry in this study, computer runs were repeated in all respects except that the subroutines which simulate the chemistry were bypassed. In effect,

Table 1. INITIAL CONDITIONS
South Montezuma Valley
(Towaoc Area)

Soil profile	B2	B3	
Ca^{++}	24	29	Meq/L
Na^{+}	52	110	Meq/L
Mg^{++}	57	51	Meq/L
HCO_3^{-}	1	2	Meq/L
CO_3^{-}	0	0	Meq/L
Cl^{-}	8	32	Meq/L
$SO_4^{=}$	118	145	Meq/L
SUMS	260	369	Meq/L
	8,369	11,940	Mg/L

Table 2. AVERAGE ANNUAL WATER APPLICATION SEQUENCE

Application No.	1	2	3	4	5	6	7	8	9
Depth (Cm)	1.37	0.33	1.60	1.14	1.02	1.27	0.51	0.38	0.13
Ca^{++}	0.75	13.26	22.77	23.85	23.85	20.84	19.34	19.24	13.05
Mg^{++}	0.09	9.68	5.54	5.91	5.13	4.98	4.51	4.60	2.63
Na^{+}	0.04	1.86	4.13	4.41	4.23	3.66	3.29	3.38	1.78
meq/L									
HCO_3^-	0.39	10.49	20.42	21.41	20.75	17.75	16.53	16.90	9.95
$CO_3^=$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$SO_4^=$	0.60	7.18	9.48	9.76	9.58	9.01	8.63	8.73	7.14
Cl^-	0.01	1.44	3.47	3.75	3.57	3.09	2.82	2.82	1.41
NO_3^-	0.00	0.05	0.08	0.09	0.08	0.08	0.07	0.07	0.05

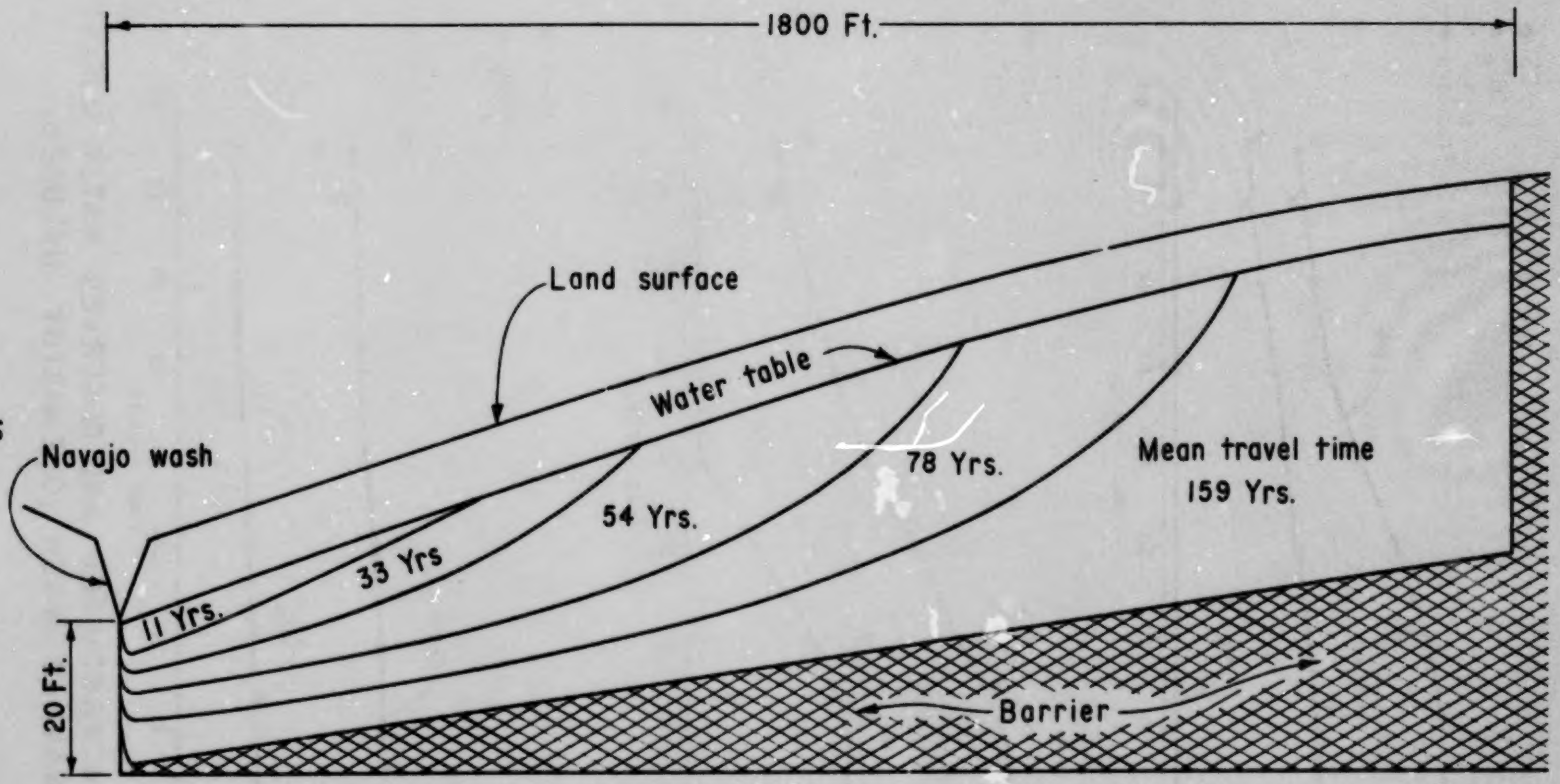
1800 Ft.
Land surface
Water table
Navajo wash
Mean travel time
159 Yrs.
78 Yrs.
54 Yrs.
33 Yrs
11 Yrs.
20 Ft.
Barrier

FIGURE 3. DIAGRAM OF FIELD APPLICATION

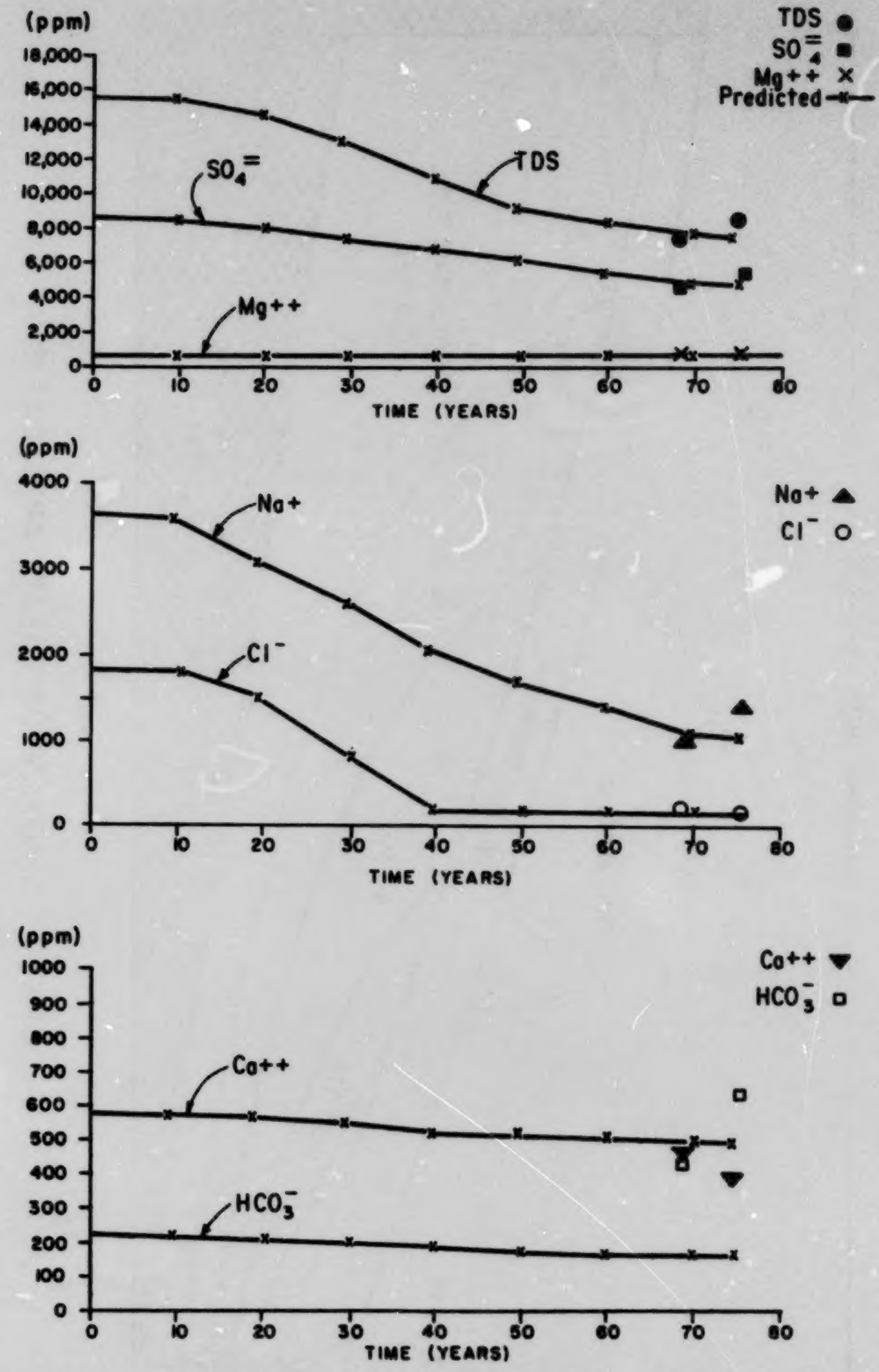

FIGURE 4. PREDICTED AND OBSERVED WATER QUALITY NAVAJO WASH (CHEMISTRY INCLUDED)

Table 3. PRESENT OBSERVED AND PREDICTED CONDITIONS (South Montezuma Area)

Soil profile	M2 (near Wash) Observed	M2 (near Wash) Predicted	M3 (farther from Wash) Observed	M3 (farther from Wash) Predicted	
Ca^{++}	25	28	23	27	Meq/L
Na^{++}	50	27	61	49	Meq/L
Mg^{++}	29	43	59	60	Meq/L
HCO_3^-	2	3	2	2	Meq/L
$CO_3^=$	0	0	0	0	Meq/L
Cl^-	3	4	10	7	Meq/L
$SO_4^=$	97	89	131	123	Meq/L
SUMS	206	194	286	268	Meq/L
	6,885	6,298	9,342	8,668	Mg/L
Percent error	8.5		7.2		
Mean percent error		7.9			

the applied waters were concentrated according to the consumptive use and routed through the system. Initial conditions were identical to those used previously.

Predicted and observed soil profile data after 75 years are given in Table 4. The prediction error increased from 8.5 to 48.2 percent in the soil closer to Navajo Wash and from 7.2 to 20.9 percent at the more distant soil location. Since the soils closest to the drain are more highly leached, the conclusion can be made that the chemical reactions become increasingly more important as leaching progresses.

However, even in the soils more distant from the discharge point, the improvement in predictive capability would easily demand inclusion of the chemistry in the simulation.

Table 4. PRESENT OBSERVED AND PREDICTED CONDITIONS
South Montezuma Area
(Chemical Reactions Bypassed)

Soil profile	M2 (near wash)		M3 (farther from wash)		
	Observed	Predicted*	Observed	Predicted*	
CA^{++}	25	20	23	25	Meq/L
Na^{+}	50	15	61	43	Meq/L
Mg^{++}	29	17	59	48	Meq/L
HCO_3	2	13	2	6	Meq/L
$CO_3^{=}$	0	0	0	0	Meq/L
Cl	3	4	10	7	Meq/L
$SO_4^{=}$	97	35	131	98	Meq/L
SUMS	206	104	286	227	Meq/L
	6,885	3,566	9,342	7,388	Mg/L
Percent error	48.2		20.9		
Mean percent error		34.6			

Predicted and observed data for water quality in Navajo Wash with the chemistry omitted from the calculations appear in Figure 5. These results indicate the prediction error increased from about 12 percent without the chemistry considered to about 28 percent without the chemistry after 70-75 years of irrigation.

A comparison of the predicted curves in Figure 5 with those in Figure 4 shows the Figure 5 TDS predictions are initially, high across the Figure 4 TDS curve, and are low in the 70-75 year period. This emphasizes the variable conclusions which can be drawn concerning the importance of the chemical reactions. It appears from this analysis that the chemistry is extremely important in most cases and should be included in the simulation.

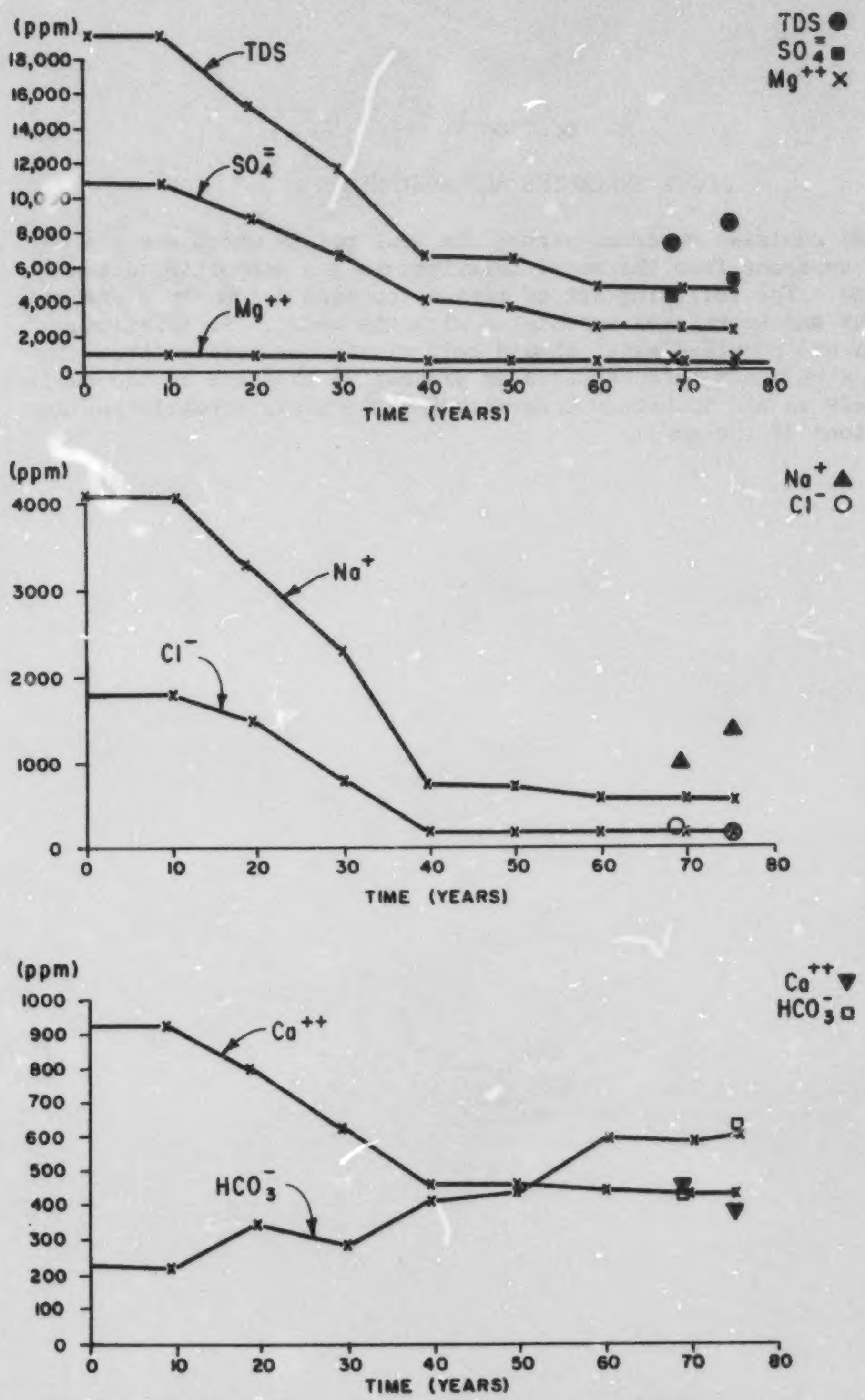

FIGURE 5. PREDICTED AND OBSERVED WATER QUALITY NAVAJO WASH (CHEMISTRY OMITTED)

SECTION V

MODEL STRENGTHS AND WEAKNESSES

The model contains numerous strong and weak points which may not be readily apparent from the model descriptions and supporting documentation. The following set of tables contains a summary of major strengths and weaknesses associated with the model. In addition, comments are provided which should help clarify certain points. The summary should not be considered an exhaustive treatise on the subject, but merely an aid to better understanding the basic capabilities and limitations of the model.

Table 5. GENERAL MODEL

Strengths	Weaknesses	Comments
The model is not directly tied to a specific irrigation system and can be used for almost any system by using the programs properly and interpreting the data inputs properly.	Different systems such as furrow and drip irrigation must be approximated and the assumptions "lived" with.	Specifics can be added to remove limitations and assumptions. Basic irrigation system design is tied into the model by efficiencies which are input to the irrigation scheduling submodel. Efficiency also relates cultural practices, crop and soil types, climatic conditions, and land slopes, etc.
The model must be applied to each specific situation encountered. Theoretically, any change in inputs requires a separate analysis.	Extrapolation to large areas involves the problem of field variability. It may be uneconomical to collect the necessary field data and make model runs.	The effect of areal variability and the sensitivity of model results to it is an item needing further research. Practically, results are more sensitive to some inputs than to others. However, relative sensitivity can change from problem to problem.
Model is built on a modular basis using subroutines and the Fortran IV programing language. It is easily expanded.	There are already a large number of subroutines and programs in the model. Knowledge of programing is also required.	Special features of Fortran compilers that are only available at one computer center have generally been avoided.
	The model is relatively complicated and expensive to run. Data requirements are considered excessive by some individuals.	Efforts to include items not presently included will tend to further complicate the model.

Table 5. (continued) GENERAL MODEL

Strengths	Weaknesses	Comments
The model simulates many important physical and chemical processes which have been identified over the years and expressed in equation form.	The model assumes away many real life complications and situations, making it unacceptable to some theoreticians. It is already so complex as to be unacceptable to many practitioners.	The model is in a "no-mans" land, and may be unacceptable to the two groups for opposing reasons. A few individuals appear to be suffering from future shock and refuse to examine this and other simulation models let alone accept them.
The following quality parameters are included in the model: Ca^{++}, Mg^{++}, Na^+, NH_4^+, NO_3^-, HCO_3^-, CO_3, Cl, SO_4, urea, organic-N, exchangable Ca^{++}, Mg^{++}, Na^+, and NH_4^+, and the ion pairs $CaSO_4$ and $MgSO_4$.	Additional quality parameters such as phosphates, pesticides trace elements, etc., are not included.	The model is open ended and additional parameters can be added. Other parameters such as ESP, SAR, hardness, etc., can be calculated from the existing parameters.
The model has several applications other than predicting the quality of return flows. Those include soil reclamation, irrigation scheduling, drain spacing design, and generating inputs to other models.	Additional applications exist which are still beyond the immediate capabilities of the model.	The model will be improved and expanded in the future.
The model is designed to allow many computer runs to be made in a short period of time.	Few guidelines are provided the user as to selection of representative input data.	Research is badly needed in this area.

Table 5. (continued) GENERAL MODEL

Strengths	Weaknesses	Comments
The model simulation begins at the soil surface and terminates at the drain (or stream).	Multiple drains/streams cannot be mixed or combined in this model.	Other models can accomplish this function (e.g. - see Volume III)
Crop uptake of nitrogen is simulated.	A fixed crop root distribution is assumed. (One can be entered for each crop.) Uptake function is crude.	A function(s) could be added making the distribution variable.
Chemical reactions are taken as a function of waterflow.	Waterflow is not considered to be a function of the chemistries.	An iterative approach could be used to add this feature.
The model includes many bypass configuration options.	The user may be confused as to which option(s) to use.	Additional model sensitivity studies could help alleviate this problem.
Model verification has been obtained for several applications.	Additional field verification would be useful.	Adequate field verification will require many years.
The model utilizes chemical equilibrium approach for inorganic (salt) reactions.	Some inorganic (salt) species may not be in chemical equilibrium.	Model verification indicates this assumption is excellent for the species considered.
Nitrogen transformations are simulated utilizing a kinetic approach.	Some rate equations are statistical and may not be valid outside derivation data set.	The transition-state nitrification equation is general.

Table 5. (continued) GENERAL MODEL

Strengths	Weaknesses	Comments
Hydrodynamic dispersion is simulated using a numerical scheme.	Dispersion is not modeled directly.	Verification data indicate the model adequately simulates hydrodynamic dispersion.
Multiple stream tubes are considered in the saturated zone.	The flow lines are taken as time invariant.	Uncertainties about aquifer properties make the current approach reasonable.

Table 6. IRRIGATION SCHEDULING SUBMODEL

Strengths	Weaknesses	Comments
Consumptive crop use is computed using the Jensen-Haise method.	Considerable data are needed to apply this method. Solar radiation data is not collected at all weather stations.	The unsaturated flow model accepts consumptive use computed by any method. It could easily be altered to accept basic data for other methods such as Blaney-Criddle. This is also true of the scheduling model.
	The effect of soil moisture on plant growth is ignored.	A plant growth model could be added, provided sufficient data are available to develop and use it.
The model makes use of concepts long accepted by soil-scientists such as field capacity, wilting point, and available moisture.	Indiscriminate use without realizing the actual physical processes involved can lead to poor results in unusual situations such as high water table conditions.	These methods have proven their usefulness. The unsaturated flow submodel tends to tie the physical situation to the older concepts of soil "constants."

Table 7. CHEMICAL EQUILIBRIA SUBMODEL (Unsaturated Zone)

Strengths	Weaknesses	Comments
Chemical equilibria subprogram simultaneously considers several chemical processes important in many Western and other soils, including solution-precipitation of lime and gypsum, cation exchange, ion pairing of $CaSO_4$ and $MgSO_4$, and pCO_2-Ca^{++}-HCO_3^- interactions.	Chemical equilibria subprogram ignores (1) other solid phases such as Na_2SO_4 and $MgCO_3$, (2) the formation of additional ion pairs, and (3) pCO_2-Ca^{++}-HCO_3^- interactions in noncalcareous soils. Ion exchange is limited to Ca-Na, Ca-Mg, and Na-NH_4^+ exchange.	The model is not applicable where solid phases other than lime and gypsum are present at chemical equilibrium and where additional ion pairs become significant. The model tests for supersaturation with respect to lime, but does not react CO_2 with the noncalcareous system. The model does not consider ion exchange in acid soils.
pCO_2 is either calculated as a function of soil moisture content or entered into the model as part of the input data.	Other functional relationships may be more useful in computing pCO_2 under situations such as within a crop root zone.	The user must input pCO_2 values within the root zone.
Activity coefficients are computed using Debye-Hückel equation generalized for monovalent and divalent ions.	Equation could be modified for each specific ion. Uncharged species are assumed to have activity coefficients equal to unity.	These approximations probably are adequate in light of other uncertainties.

Table 8. NITROGEN TRANSFORMATION SUBMODEL (Unsaturated Zone)

Strengths	Weaknesses	Comments
Simultaneously considers nitrification, urea hydrolysis, mineralization, immobilization, NH_4^+ ion exchange, and denitrification (saturated zone only).	Ignores nitrogen fixation, ammonia volatilization, denitrification (unsaturated zone).	Fixed nitrogen can be added to soil as input data.
Nitrogen transformation rate equations include important variables such as substrate concentrations, temperature, soil moisture content, etc.	Most rate equations were derived statistically based on experimental data from a limited number of soils. Extrapolation to other soils may be dangerous.	Transition state nitrification equation is general.
Nitrification is simulated using either a statistical equation, or a transition state equation. Transition state equation includes pH, partial pressure of O_2, osmotic effects, and NH_4^+ concentrations as variables.	Statistical equation may be limited to certain soils. Transition state equation is general but applies only to soils with fixed microbial populations. Microbial population is assumed to be fixed in size.	Transition state equation could be extended to include variable microbial population size.

Table 9. NITROGEN UPTAKE SUBMODEL

Strengths	Weaknesses	Comments
Nitrogen uptake by the crop is allowed in the form of NO_3^- and NH_4^+.	A fixed ratio between the uptake of these two species is used. Uptake of other N species is not considered.	A variable ratio could be added at a future time. The major N species taken as by plants are NO_3^- and NH_4^+.
Total nitrogen uptake can either be inputed to the model on a semimonthly basis or computed by assuming that N uptake is proportional to consumptive use. (The user supplies the proportionality constant.)	Additional nitrogen uptake functions or schemes are not considered.	The model is not yet particularly sophisticated in its handling of crop N uptake. This submodel will be improved in the future.

Table 10. SALT MOVEMENT SUBMODEL (Unsaturated Zone)

Strengths	Weaknesses	Comments
Unsaturated waterflow volumes as computed by the Unsaturated Flow Program are used to move soluble salts into and from each soil segment (both in upward and downward direction).	Mechanical dispersion is not simulated directly.	The use of several soil segments per profile tends to introduce numerical dispersion. This technique has yielded good correlations with observed data in unsaturated lysimeter tests.
	Lateral movement of salts is not considered.	
Soil chemical reactions are included in the leaching process at each step in time and space.	Some waterflow rates may be too high to allow chemical equilibrium as assumed in the model.	

Table 11. UNSATURATED FLOW SUBMODEL

Strengths	Weaknesses	Comments
Unsatured waterflow is simulated in the upward and downward directions.	Two- and three-dimensional flows are not considered. Consequently, the model is not directly applicable to trickle and furrow irrigation.	Additional dimensions could be added but with increased computer storage requirements and costs.
The bottom boundary is taken as the water table.	The geometric location of the water table is not changed.	This tends to overestimate the upward movement of water by capillary forces when plant-induced gradients produce such flow. A moving water table location could be modeled.
Consumptive use is computed using either the Jensen-Haise or Blaney-Criddle methods.	Other methods may be more desirable.	They can be added to the irrigation scheduling or unsaturated flow models or to both.
Hysteresis in the conductivity and diffusivity relations is ignored, simplifying program use and reducing input requirements.	Hysteresis, especially in the diffusivity, has been considered by many investigators as important in "wetting-drying" systems.	Inclusion in the model is possible, although it would complicate programing, increase computer storage, and lengthen runs. Adequate field data to run the model would be almost impossible to obtain.
Water is extracted from the root zone according to a specified root pattern, using a root extraction term.	The root distribution is constant with time.	A variable root pattern could easily be added. It could be a function of time or be based on a more complicated model of plant growth (as influenced by temperature, availability of water, and the salinity of the soil water). Field data would be costly.

Table 12. DRAINOUT SUBMODEL

Strengths	Weaknesses	Comments
USBR drainage equations are utilized.	Approximations associated with USBR techniques are included.	USBR drainage equations have seen a wide application in the United States and foreign countries.
Submodel will either predict the response of a given drainage system to deep percolation inputs or estimate the drain spacing based on system physical properties and desired drainage depth.		Model duplicates USBR method for designing lateral spacings and consequently is accepted by drainage personnel.
Submodel computes the monthly drain discharges.	User may want discharges over some alternate time period.	Daily discharges are actually computed by the model and can be listed or plotted as output. They are available in the special plot file generated by the program.
Homogeneous, isotropic conditions are modeled. This allows use of relatively simple mathematics that are economical for computer calculation.	Real situation involves heterogeneous conditions. See comments.	Weighted permeabilities with depth are used to account for variability of soils. The storage coefficient corresponds to a weighted value in the zone of water table fluctuations.

Table 13. SATURATED FLOW SUBMODEL

Strengths	Weaknesses	Comments
Submodel calculates the steady-state position (and corresponding flow tube volumes) of stream lines extending from the water table to the drain, using potential flow theory.	Stream lines occupy fixed positions as opposed to the variable situation in the field.	This approximation probably is suitable in light of other uncertainties in the saturated zone. The Dupuit-Forchheimer assumptions are not invoked.
Submodel calculates the mean travel times for flow through each tube.	The travel times are based on the computed Darcy velocity divided by the porosity. The porosity is based on volumetric considerations and not on cross-sectional areas.	Research in this area has indicated that use of the porosity yields good results (within a few percent) when compared to actually measuring areas of flow. This is true, even for very tight, clay soils.
Submodel simulates flow through a homogeneous, isotropic aquifer.	Real aquifers are not homogeneous and isotropic.	A submodel capable of simulating a multilayered aquifer would be desirable at some future time.
Two-dimensional flow simulation includes flow to subsurface, tile drains.	Three-dimensional flow and radial flow to wells are not included.	The basic techniques are applicable to any geometric flow system. Analytical solutions are desirable as they are cheaper to use with the computer. However, numerical solutions could be used to simulate very complex problems.

Table 14. SATURATED CHEMISTRY SUBMODEL

Strengths	Weaknesses	Comments
Simulates inorganic chemistry and denitrification in the saturated zone.	Acid soil chemical reactions not included. Denitrification submodel is very crude.	These deficiencies will be corrected in the future.
Flow through each stream tube is considered to be via complete piston displacement.	Flow in the field does not strictly follow this pattern.	Verification data indicate this approximation is suitable.
Mechanical dispersion is simulated by including multiple-tube elements.	Mechanical dispersion is not not modeled directly.	Verification data indicate model approximation is suitable.
Inorganic chemical reactions at each point in space.	Contact times near the drain may be too small to allow chemical equilibrium to be achieved.	Other uncertainties probably overshadow this approximation.
Submodel has many options such as salt injection at the barrier, simulation of unsaturated chemistry, etc.	User may not be completely aware of all the options.	The Saturated Chemistry user's manual describes the options.

Table 15. DRAIN EFFLUENT SUBMODEL

Strengths	Weaknesses	Comments
Combines water from each flow tube to form the drain water quality mix.	Water quality mix is not reacted chemically and could be unstable from a chemical standpoint.	
	Submodel requires considerable computer memory for runs involving many years of simulation.	This program could be redone using a different programing approach to remove this limitation.

SECTION VI

SUMMARY OF REQUIRED INPUT DATA

From the preceding model description, it is apparent that many physical and chemical parameters are required for input to the model. Most of this information is routinely collected or developed in planning and designing an irrigation project. All of the required field data are listed below:

DRAINAGE DESIGN

The geometry of the drainage system must be specified including:

a. Drain spacing.

b. Depth to drains.

c. Depth to barrier.

d. Gravel envelope size or design, used to determine the effective radius.

SATURATED MATERIAL PROPERTIES

Saturated material properties should correspond to values used in designing the drainage system and consequently represent average values for the assumed homogeneous system. These properties include:

a. Saturated hydraulic conductivities (permeabilities).

b. Porosity.

c. Specific yield or storage coefficient.

UNSATURATED MATERIAL PROPERTIES

In order to simulate unsaturated flow, the following material properties must be known:

a. Hydraulic conductivity (permeability) as a function of moisture content.

b. Moisture release curves (tension head versus moisture contents).

Direct measurement of the unsaturated hydraulic conductivity by field or laboratory methods is difficult, time consuming, and expensive. A limited number of such determinations have been reported in the literature. Consequently, in lieu of direct measurements, an approximate procedure known as Millington-Quirk Method (9) can be used.

This approach recognizes that unsaturated conductivity is related to pore-size distribution. The moisture release curve is used in conjunction with a semiempirical equation. To assure that the computed and measured conductivity agree at least at one point, a matching factor is used. For practical purposes, it is computed as the ratio of the measured to the computed conductivity at saturation. The technique is simple enough to allow the determination of the spatial variability of conductivity.(15) In using the method, moisture contents should be determined for tensions between 0.05 and 15 atmospheres. Enough points should be used to adequately determine the shape of the curve.

SOILS ANALYSIS

Master site soils data should provide the following chemistry data:

Soil extract data:

a. Cations (meq/l of calcium, magnesium, and sodium).*

b. Anions (meq/l of carbonate, bicarbonate, chloride, and sulfate).

c. Extract ratio of water to soil.

d. If nitrogen is considered, the meq/l of ammonium, nitrate, and urea.

Additional data:

a. pH.

b. Cation exchange capacity in meq/100 g of soil.

c. Gypsum content in meq/100 g of soil.

d. Indication if soil is calcareous (line present) or not.

e. Bulk density in g/cm^3 of soil.

f. If nitrogen is of interest, the organic nitrogen content in micrograms/g of soil and the corresponding carbon-nitrogen ratio;

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* In this report meq denotes millequivalents, meq/l denotes milliequivalents/liter and mg/l or mgm/l denotes milligrams/liter. Also cm^3 is cubic centimeters, cm is centimeters, and g is grams.

for use in the transition-state nitrification model, nitrifier-population salt response relationship.

Normally, these data are collected in 12-inch intervals or some other suitable scheme down to the barrier. The unsaturated chemistry program accepts these data horizon by horizon while the saturated chemistry program uses a single or average analysis.

CROP INFORMATION

The different types of crops grown in the area to be studied should be determined and similar crops grouped. If predictions are to be made for the entire area, the associated acreage for each group should be available. For each group, the following information must be obtained:

a. Growing season.

b. Root zone depth and root distribution within the zone.

c. Evapotranspiration rates (if irrigation scheduling is used, solar radiation and temperature; planting, cover and harvest dates; cutting dates if alfalfa is included; cutoff date beyond which irrigations are not allowed; thaw and freeze dates for the soil; initial soil moisture in root zone on the thaw date; and the percent soil moisture in the root zone that may be used before an irrigation is required).

d. Plant uptake of nitrogen (if nitrogen is considered).

WATER APPLICATIONS

The following data are needed to characterize the water volumes entering the soil-aquifer system:

a. Irrigation schedules and amounts (for model purposes only that component entering the soil system is used).

b. Days on which precipitation occurs and the corresponding amounts (for model purposes only that component entering the soil system is used).

c. Effective precipitation relationship.

FERTILIZER INFORMATION

Additions of chemicals by fertilizer applications may be included. If they are, necessary inputs include:

a. Fertilization schedules.

b. Amounts of constituents in chemical fertilizers (amounts in lb/acre of nitrate, ammonium, urea, calcium, sulfate, and carbonate).*

c. Depth if plowed in or surface application indicated for each application of a chemical fertilizer.

d. For each organic nitrogen application the depth of plow down (no surface application allowed), carbon-nitrogen ratio, and the application rate in lb/acre.

IRRIGATION WATER ANALYSIS

The chemical analysis of the irrigation water in meq/l of NH_4^+, NO_3^-, Ca^{++}, Na^+, Mg^{++}, HCO_3^-, Cl^-, $CO_3^=$, and $SO_4^=$ must be supplied to the program.

SOILS TEMPERATURE DATA

If nitrogen is to be considered, soil temperatures as a function of depth and time are required. The nitrogen transformations are temperature dependent.

SOILS COEFFICIENTS

Soils coefficients relating to nitrification and denitrification must be inserted into the model.

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* Note: This input option can be used to add gypsum to the soil.

SECTION VII

INTERFACING WITH CONJUNCTIVE USE MODEL

The return flow quality simulation model described in Volume V is designed to provide, among other outputs, water flow and quality predictions in a tile drain or stream. Combination (mixing) of two or more drains or streams is currently beyond the scope of the model. This capability could easily be added in the future. The conjunctive use model (Volume III) can supply this additional mixing or nodal capability provided a suitable model interface is done.

The soil (unsaturated) portion of the conjunctive use model can be bypassed in favor of the more sophisticated unsaturated flow and chemistry programs available in the Volume V model. Also, if the user wishes to simulate nitrogen transformations, he must utilize Volume V.

The "tank" type aquifer simulation in the conjunctive use model can be bypassed in a similar manner in favor of the more detailed saturated flow and chemistry simulations available in the Volume V model.

The user must decide which model or model combinations best fit his particular application. Applications exist in which one entire model should be applied, while others would best be handled by some combination of models.

The details of interfacing these two models are left to the user. The problem is basically one of converting output files to the current format and time frame for input to the other model. Small interfacing programs such as the Interface for Chemistry Program will be needed. The user should consult the appropriate user's manuals for details concerning the proper input/output files.

SECTION VIII

USER'S MANUAL - OVERALL MODEL

INTRODUCTION

This manual discusses details and procedures common to the model as a whole. Data interfacing between subprograms, bypass options, and general tips on model application and operation are given.

The model is fully operational on the Bureau of Reclamation CDC CYBER 74-28 computer located in Denver, Colorado. This computer is highly time-share oriented with permanent disk storage available to the user. On this type system, linkage between subprograms within the model can be done easily and the entire model operated from a remote terminal. The model can also be run on batch computer systems, but more user effort is required.

SUBPROGRAM LINKAGE

After the basic input data have been entered into the computer, interfacing between subprograms is accomplished via binary data files. These files generally are stored either on magnetic tape or on permanent disk storage, if available. Output and input formats have been structured to allow direct interfacing without user intervention. The user need only direct the particular submodel to read the appropriate binary file(s) created by the previous program. Specific discussions of each file are included in the appropriate user's manual. Should the user find it necessary to examine these binary files, a suitable program can be written to read and print them.

BYPASS OPTIONS

A user may not have the data or require the detail associated with some models subprograms. The following discussion summarizes bypass options which have shown utility.

Irrigation Scheduling

The irrigation scheduling submodel can be bypassed if the user inputs pertinent data to the Unsaturated Flow and Drainout Programs. This includes crop evapotranspiration data (p. 79) and irrigation and precipitation dates and amounts in the case of the Unsaturated Flow Program (p. 77). An option (CRØP, p. 76) in the Unsaturated Flow Program allows estimation of crop consumptive use by the Blaney-Criddle method but is limited to a few crops programed into the model. The Drainout Program requires data on deep percolation amounts from precipitation and irrigation. These can be supplied from the Irrigation Scheduling Program or some other source.

Unsaturated Flow And Unsaturated Chemistry

These two submodels tend to be large consumers of computer execution time. However, they are highly sophisticated programs which consider many details (including nitrogen transformation and inorganic chemical under nonsteady- and steady-state flow conditions). The unsaturated chemistry submodel requires input from the Unsaturated Flow Program or a similar source if nonsteady flow is to be considered. An option in Unsaturated Chemistry (ITEST=1, p. 143) allows input of steady-state flow and moisture content data from cards. In this case, additional flow and soil moisture content data are not needed.

Bypassing of both the unsaturated flow and unsaturated chemistry submodels can be done quite easily via card input to the Saturated Chemistry Program. In this case, both quantity and quality of waters must be specified. The user either enters values for the volume and quality of the deep percolation water or specifies similar values for water entering at the soil surface together with the onfarm irrigation efficiency. In the latter case, the program adjusts both quantity and quality in proportion to the efficiency.

There is no direct option which allows input of data to the Saturated Chemistry Program from the Unsaturated Flow Program. If Unsaturated Flow is utilized, Unsaturated Chemistry must be used to generate input to Saturated Chemistry. Another program could be constructed to take unsaturated flow output from Unsaturated Flow, assign qualities to these flows, and punch a card deck suitable for input to the Saturated Chemistry Program.

The user should note that a bypass of Unsaturated Chemistry bypasses the nitrogen transformations in the unsaturated zone. There is no alternate means of simulating these reactions within the model. It is possible to use the Saturated Chemistry Program to simulate salt reactions in the unsaturated zone. In this case, some characteristic leaching moisture content(s) is specified in place of the saturated value(s). Each tube in Saturated Chemistry then represents a specific soil profile and each tube element becomes an unsaturated soil segment.

Additional options in Unsaturated Chemistry allow the nitrogen transformations and salt reaction portions to be individually bypassed.

Thus, it is possible to consider nitrogen transformations and movement without the salt reactions. Conversely, salt reactions and movement can be simulated without the nitrogen transformations.

Saturated Chemistry

This submodel is not needed if the simulation is terminated at the water table and the program is not being used to simulate chemistry in the unsaturated zone. It is possible to use Saturated Chemistry as purely a routing-type model with no salt chemical reactions considered. In this case, SBYPAS (p. 183) is set equal to one. This option is extremely useful in cases where only nitrogen species are being considered in the saturated zone. If IDN (p. 183) is set equal to one, a denitrification subroutine is called from Saturated Chemistry. If the parameter equals zero, the subroutine is bypassed.

Another option in Saturated Chemistry allows injection of salts at the barrier. In this case IINJE (p. 183) is set equal to one, and additional data (Card Group 4, p. 186) must be inserted into the input deck. This option allows salts to be added into the system from a source such as a shale bed. Fick's Law is utilized.

Still other options in Saturated Chemistry allow user inputed values for ion exchange coefficients and CO_2 partial pressures. Appropriate sections of the user's manual should be consulted for details.

Drain Effluent Prediction

The submodel can be bypassed any time there is no need to mix waters from the various saturated flow tubes. This can occur when the simulation is terminated at the water table, when drain discharges without any associated qualities are being simulated, or when effects on the aquifer are desired independently of drain quality.

The Drain Effluent Prediction Program must be utilized if quality predictions at the drain are desired.

Saturated Flow

The Saturated Flow Program can be bypassed if values for flow tube volumes and top widths can be determined from alternate sources. These could be estimates or other simulation models. The program is not needed if only monthly drain discharges with no associated qualities are the objective. In the latter case, these values are output from the Drainout Program.

TIPS ON MODEL APPLICATION

Use Of Bypass Options

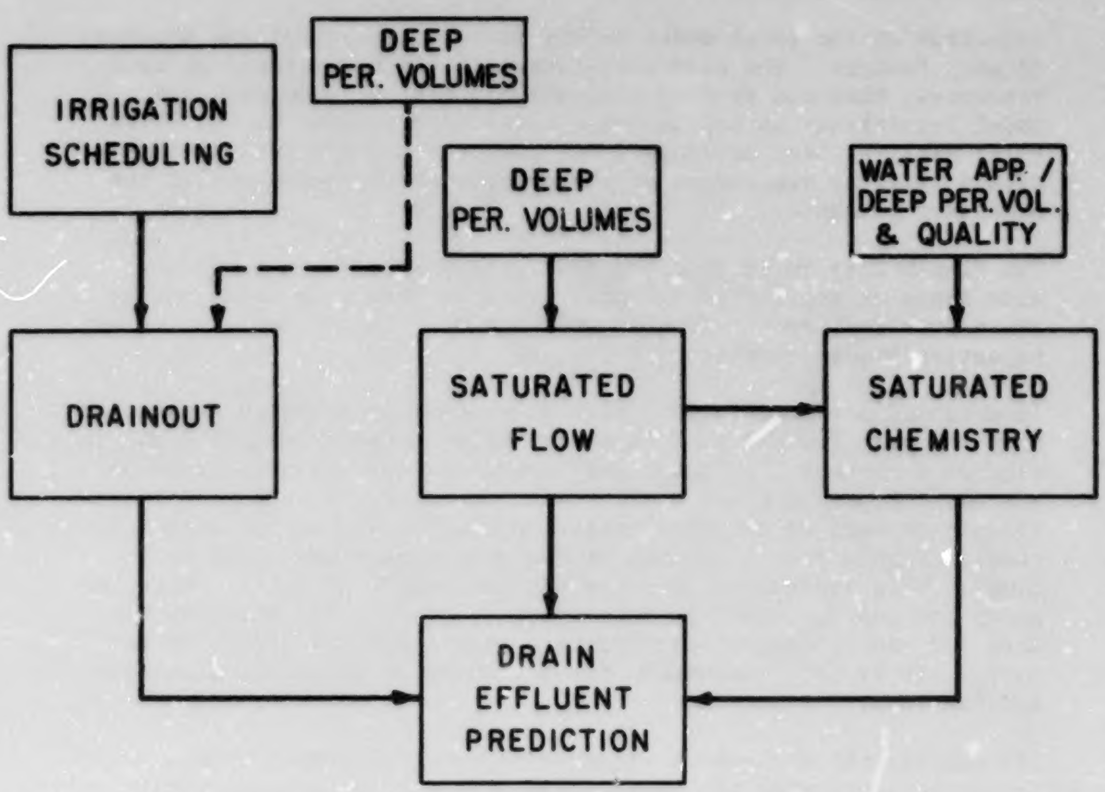
Selection of the total model or one or more bypass options depends on many factors. The user must determine his needs based on data resources, time and funding allocations, desired accuracy, and model sensitivity as applied to a particular situation. No fixed rules have yet been developed, but common sense applied together with a critical evaluation of the problem should help provide the necessary guidance.

The flexibility built into the model was placed there to allow a wide range of applications. However, care should be taken not to abuse this feature. A program sequence used in one application may be entirely inappropriate for another.

Several model configurations have shown utility based on experience over the past few years. These are illustrated in Figure 2 and in Figures 6 through 11. Additional sequences are possible based on the model bypass options available to the user. The sequences shown illustrate some of the more common applications possible with this model. Figure 2 contains all of the subprograms contained in the model. This sequence allows the maximum amount of detail which the model can supply. This configuration is recommended whenever the data and study requirements indicate that a maximal effort be put forth. It is not recommended for screening or reconnaissance-type applications.

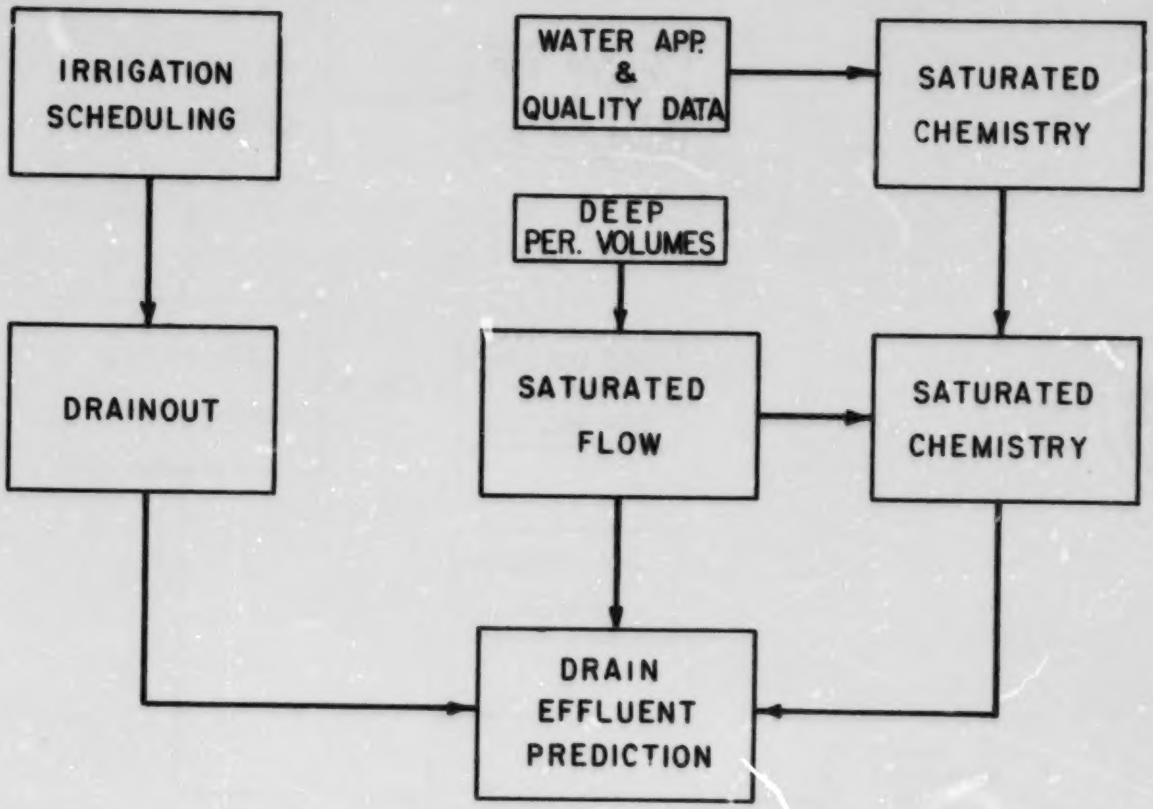
The configuration shown in Figure 6 is a useful computer time-saving sequence when the unsaturated zone can be ignored. This can occur when relatively "clean" surface soils are encountered, nutrients are not being considered, and "ball park" type answers are wanted for large acreages. With this sequence, many computer runs can be made at a low cost. No information can be obtained concerning chemical changes in the unsaturated zone (e.g., the location of salt precipitation within the unsaturated zone cannot be determined).

Figure 7 contains a configuration which is similar to that in Figure 6 except that piston flow at a constant 'leaching' moisture content is considered in the unsaturated zone. The Saturated Chemistry Program is used to simulate salt reactions (no nutrient transformations) in the unsaturated region. It generates output which can again be inputed to the same program but at the saturated moisture content. This arrangement uses only slightly more computer time than that in Figure 6 and includes simulation in the unsaturated zone.


DEEP PER. VOLUMES
IRRIGATION SCHEDULING
DEEP PER. VOLUMES
WATER APP. / DEEP PER. VOL. & QUALITY
DRAINOUT
SATURATED FLOW
SATURATED CHEMISTRY
DRAIN EFFLUENT PREDICTION

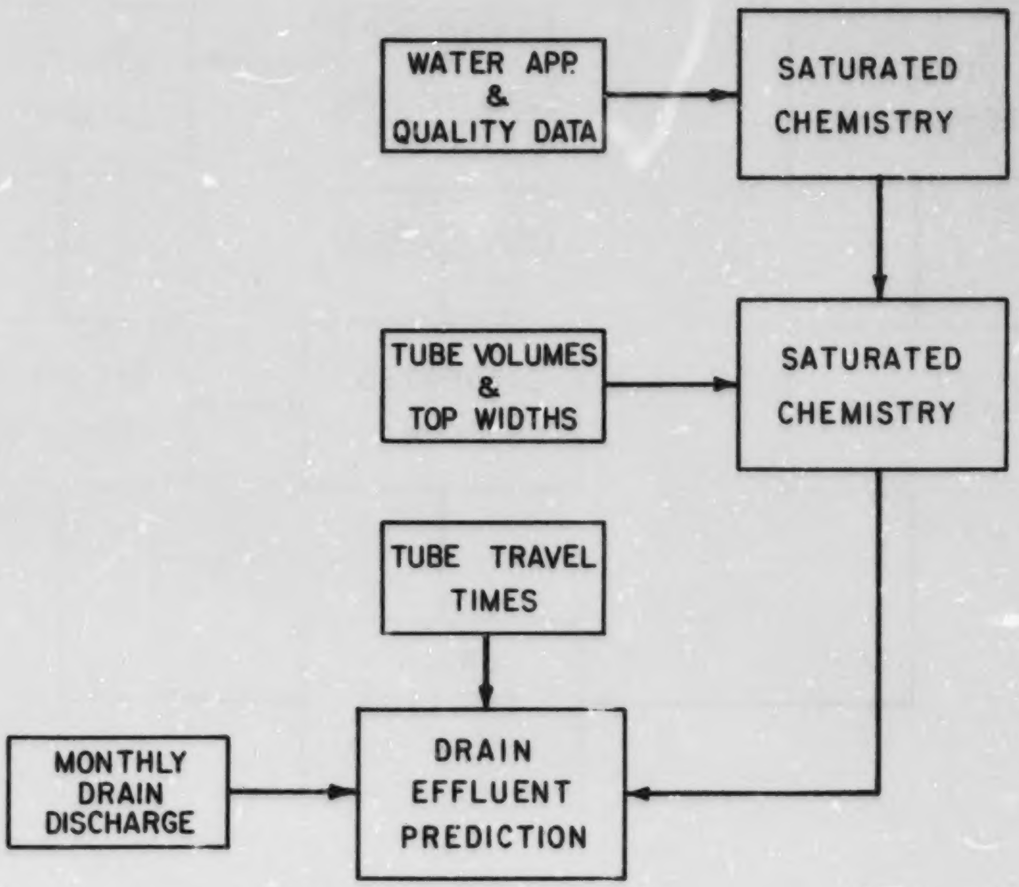
Assumes chemistry and flow in the unsaturated zone have insignificant effects on quality of drain effluent. Irrigation scheduling may be utilized or by passed.

FIGURE 6. MODEL BY PASS CONFIGURATION NO. I


IRRIGATION SCHEDULING
WATER APP. & QUALITY DATA
SATURATED CHEMISTRY
DEEP PER. VOLUMES
DRAINOUT
SATURATED FLOW
SATURATED CHEMISTRY
DRAIN EFFLUENT PREDICTION

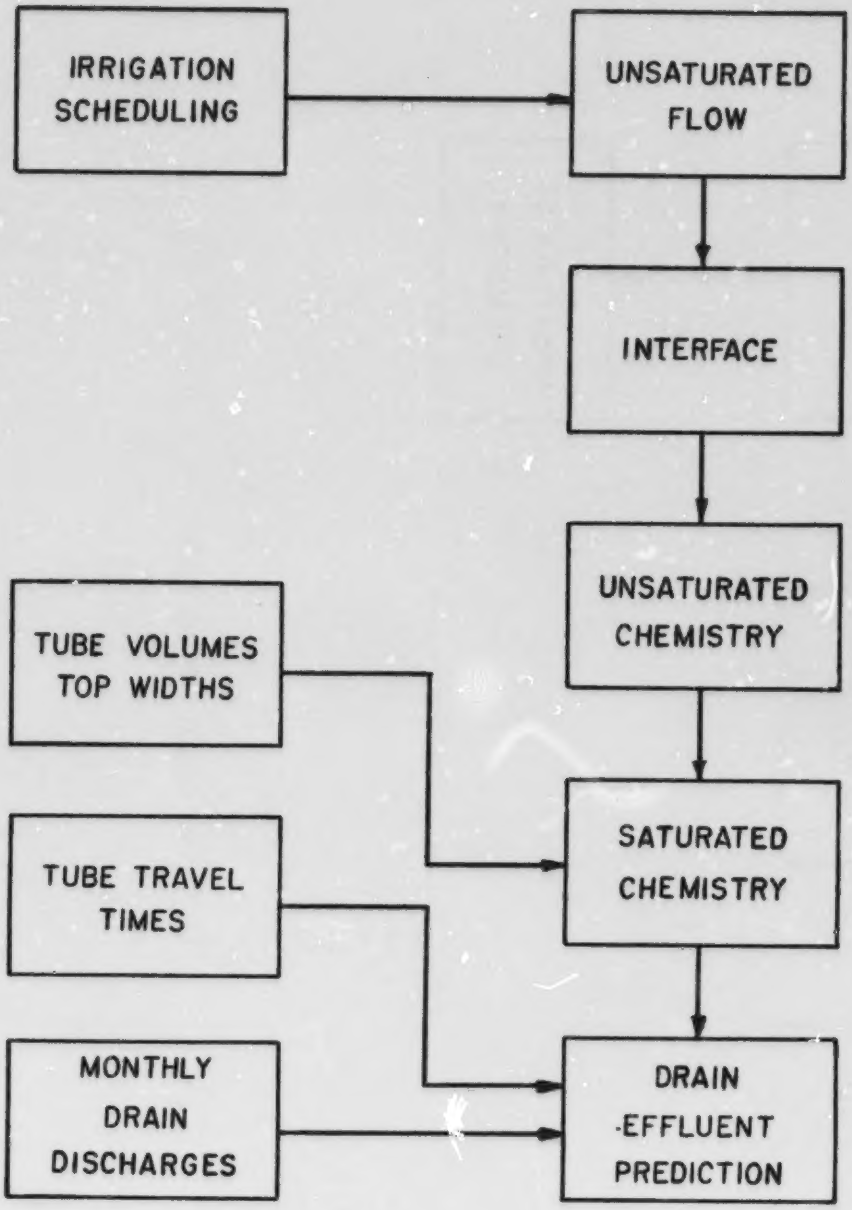
More crudely approxmates unsaturated flow by assuming leaching takes place by piston displacement at some constant leaching moisture content.

FIGURE 7. MODEL BY PASS CONFIGURATION NO. 2


WATER APP.
&
QUALITY DATA
SATURATED
CHEMISTRY
TUBE VOLUMES
&
TOP WIDTHS
SATURATED
CHEMISTRY
TUBE TRAVEL
TIMES
MONTHLY
DRAIN
DISCHARGE
DRAIN
EFFLUENT
PREDICTION

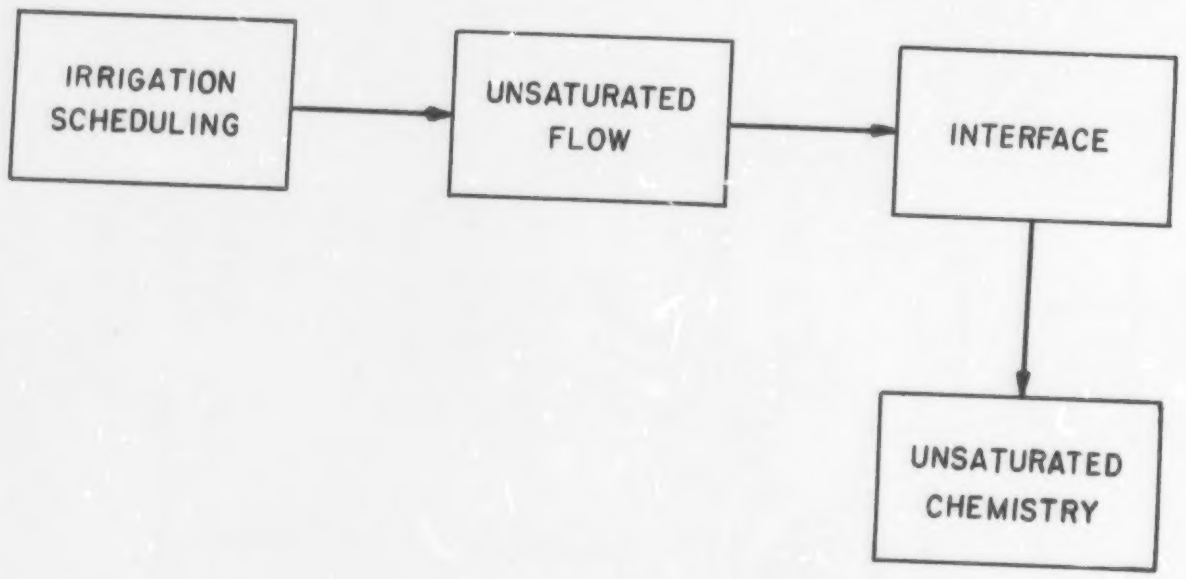
All water flow parameters must be estimated or obtained from another source. Chemistry routines utilized whenever possible.

FIGURE 8. MODEL BY PASS CONFIGURATION NO. 3


IRRIGATION SCHEDULING
UNSATURATED FLOW
INTERFACE
UNSATURATED CHEMISTRY
TUBE VOLUMES TOP WIDTHS
SATURATED CHEMISTRY
TUBE TRAVEL TIMES
MONTHLY DRAIN DISCHARGES
DRAIN EFFLUENT PREDICTION

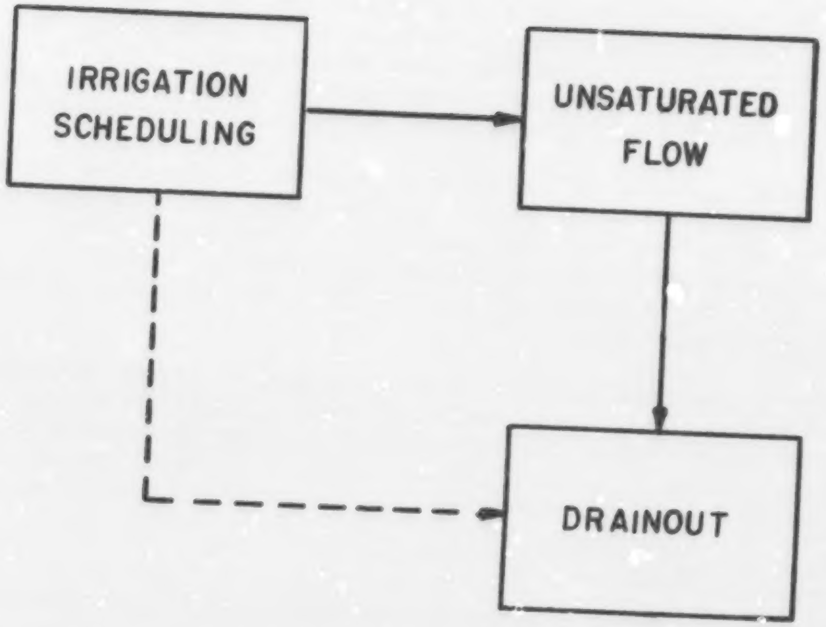
Considers salt and nitrogen chemistry in unsaturated zone. Groundwater flow parameters estimated

FIGURE 9. MODEL BY PASS CONFIGURATION NO. 4


IRRIGATION SCHEDULING
UNSATURATED FLOW
INTERFACE
UNSATURATED CHEMISTRY

Detailed unsaturated zone

FIGURE 10. MODEL BY PASS CONFIGURATION NO. 5


IRRIGATION SCHEDULING
UNSATURATED FLOW
DRAINOUT

Allows design of drainage system using either output from Unsaturated Flow or deep percolation values from Irrigation Scheduling.

FIGURE II. MODEL BY PASS CONFIGURATION NO. 6

Figure 8 illustrates a sequence which is useful when flow through large aquifers to open drainage channels such as stream and rivers is being modeled. In this case, the user inputs estimates for all the flow parameters and utilizes a simplified chemistry sequence. Nitrogen transformations in the unsaturated zone cannot be modeled.

The configuration in Figure 9 is somewhat similar to the one in Figure 8 but allows nutrients as well as salts to be considered when groundwater flow parameters must be estimated. In this case the unsaturated flow subprogram must be included for nonsteady flows, and the irrigation scheduling subprogram is recommended.

Figure 10 illustrates an abbreviated sequence which allows maximum detail in the unsaturated zone. This is useful when the effects over time of various cultural practices are desired. Effects of high irrigation efficiencies, gypsum applications, high salinity and/or high sodium irrigation waters, etc., can be tested in some detail in the root zone.

The abbreviated configuration shown in Figure 11 allows design of drain spacings given porous media properties, depth to barrier, effective drain radius, depth to drains, and the deep percolation schedule. Irrigation scheduling can be used to input monthly deep percolation volumes into drainout, thus bypassing unsaturated flow.

Intermediate Output

The model is composed of several subprograms which have been interfaced. Thus, intermediate results are generated at various stages during a simulation run. The user should take particular care to examine some of these results (not necessarily the entire binary interface files) and make certain he is satisfied before proceeding to the next step. Often an error has been made somewhere in the input data or assumptions. If an error is present, early detection could avoid a costly rerun of some or all of the model. Check the results (intermediate and final) against your experience and judgment and any verification data which may be available. Never trust results merely because the computer has generated them. Garbage (data and assumptions) into a machine always equals garbage out, and good inputs and assumptions yield qualified predictions.

Printed Output Volume

The output options in the model allow the generation of large volumes of printed output. Although a certain amount is needed to verify intermediate results and list the final answers, an attempt should be made to minimize the volume. Output can be dumped to magnetic tape or microfiche in lieu of printing, but again the question should be asked, "Is all this really necessary?"

Accuracy Versus Computer Run Times

Within the model, several parameters are specified which allow the user to increase the accuracy of the results at the expense of computer execution times. In most cases, a range of values is listed to give the user an idea of what numbers to select. The user must use his own judgment as to what accuracies are demanded in his particular application. Some experimentation may be necessary to more closely refine some of these criteria.

Conversion To Other Computer Systems

The computer model as listed in Volume V is operational on a CDC CYBER 74-28 machine under the FORTRAN Extended Compiler. Conversion to other CDC 3000, 6000, and 7000 series computers should be possible with a minimum of problems. Conversion to machines such as IBM and Univac is possible, but a number of difficult conversion problems can be expected. The user should use the test run included in this volume as a check on the validity of his particular conversion.

Some consideration should be given to utilizing this model on the Bureau of Reclamation computer system. A remote terminal can be tied into the system and used to run the model with a minimum of effort. In addition, Bureau personnel can readily assist with any program difficulties.

SECTION IX

USER'S MANUAL

IRRIGATION SCHEDULING PROGRAM

INTRODUCTION

This program computes irrigation schedules using daily historic precipitation, temperature and solar radiation data, and associated crop and soil data. Crop evapotranspiration is computed using the Jensen-Haise procedure (7,8). Irrigation dates and amounts are determined on the basis of a soil moisture budget accounting procedure.

If desired, a file containing crop evapotranspiration data and precipitation and irrigation applications can be written in a format suitable for input to the Unsaturated Flow Program via an interface utility routine.

Likewise, a file containing deep percolation amounts from rainfall and irrigation can be written in a format suitable for input to the Drainout Program via an interface utility routine.

For comparative purposes, weighted-average, monthly irrigation information can be computed from the irrigation events for each crop. These values can then be compared with a monthly summary of irrigation events computed using the weighted evapotranspiration values from all crops. The program reads on file 2 (input) and writes on files 3, 4, 5, and 6 (output). The FORTRAN program requires about 240,000 octal words on the Bureau computer. The storage locations in the computer must be set to zero before loading this program.

DATA INPUT CARD SEQUENCE AND DATA LIMITATIONS

CARD GROUP 1

Column No.	Var type*	Var name	Variable description
Card 1 of 5			
1- 5	A	IZIP	Zip code for study area.
6	X	-	Region number.

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* Note: A is alphanumeric.
R is real (floating point).
I is integer (fixed point).
X is blank or space.

Column No.	Var type	Var name	Variable description
7-36	A	ILOCA	Name and/or location of study areas.
37-42	R	ELEV	Elevation of study area.
45	I	NELFLG	Flag for using elevation in computing Jensen-Haise coefficients. 0 = Use elevation. 1 = Do not use elevation.
(The following 10 columns not used.)			
46-48	I	LATDEG	Latitude of study area in degrees.
49-50	I	LATMIN	Latitude of study area in minutes.
51-53	I	LONGDG	Longtitude in degrees.
54-55	I	LONGMN	Longitude in minutes.
79-80	X	-	Card number.
Card 2 of 5			
1- 6	X	-	Zip and region.
7-72	A	IUSBR	Descriptive information on study area.
79-80	X	-	Card number.
Card 3 of 5			
1- 6	X	-	Zip and region.
14-15	I	NOYRS	Number of years of climatic input data. Maximum of 30 years. Note: When the solar radiation data are not taken at the study site, the following should be applied to data - (ARS,BRS).
16-20	R	ARS	Slope of linear regression equation to transfer solar radiation from one location to another.
21-25	R	BRS	Intercept of linear regression equation. RS = RS*ARS + BRS.

Column No.	Var type	Var name	Variable description
30	I	NCPTS	Number of combinations of weighted crop percents. Min = 0 (if NCPTS = 0, do not include Card 4). Max = 5.
31-35 36-40	R R	PCTWPB PCTWPC	Percent of winter snow that enters the soil at the time of soil thaw. The remaining percent of the snow is considered runoff. Note: Winter precipitation has daily evaporative demand subtracted; the remaining precipitation is summed throughout the winter (carried over from 1 year to the following year) and the accumulated value used at soil thaw. PCTWPB is percent for bare ground. PCTWPC is percent for ground with cover such as alfalfa or pasture.
52	I	IPUNCH	Flag for writing precip, irr, and ET on file 4 in a format suitable for input to the unsaturated flow program. (Interface utility.) If card output is desired, cards may be punched from file 4. 0 = No write. 1 = Write.
54	I	IFLGCL	Flag for printing climatic data (file 3). 0 = No print. 1 = Print.
56	I	IFLGIR	Flag for printing irrigation schedules by year and by crop. 0 = No print. 1 = Print. Note: If both IFLGCL and IFLGIR are zero, only a summary will be printed which shows annual values for all years for each crop.

Column No.	Var type	Var name	Variable description
58	I	IWIDTH	Flag for width of printout of irrigation schedules. 0 = 132-column printout. 1 = 72-column printout.
60	I	ICARYO	Flag for carrying over soil moisture and winter precipitation to the following year. 0 = No carry-over. 1 = Carry-over. Note: If ICARYO = 1, NDB and NDE should be 1 and 366, respectively.
62	I	IWTDP	Flag for writing deep perc from rain and irrigation in format for input to Drainout Model. 0 = No write. 1 = Write.
64	I	IWTIR	Flag for computing weighted monthly irrigation parameters. Note: This weighted average computed by irr event was done to compare weighted et values from all crops. An annual summary is written on file 6 when this flag is set. 0 = Annual summary not printed. I = Annual summary printed.
66	I	IWTIRD	Flag for printing detailed event by event monthly summary of irrigation weighted information on file 6. 0 = Detailed summary not printed. I = Detailed summary printed.
Card 4 of 5			
79-80	X	-	Card number.
1- 6	X	-	Zip and region.

Column No.	Var type	Var name	Variable description
16-45	R	CPCT	The percentage of each crop acreage to the total acreage, as it appears chronologically in card 9, three columns per value, maximum of 10 values (10 crops).

Card 4 is repeated for each combination of weighted crop percents. There should be the same number of these cards as NCPTS.

Card 5 of 5

1-15	X	--	Zip, region, and other ID.
16-40	I	IPAR	Flag for type of irrigation parameter to be weighted and printed in monthly format. If IPAR = 0, do not do it. If IPAR = 1, do it. Place the flag in the proper column, see following list. Col parameter: 16 Evapotranspiration 18 Precipitation 20 Precip runoff 22 Precip entering soil 24 Precip deep percolation 26 Soil moisture added by precip 28 Net et (et reqt to be met by irr) 30 Total irrigation application 32 Drift loss from sprinkler 34 Runoff loss from gravity irr 36 Irr appl infiltrating the surface 38 Soil moisture added from irrigation 40 Deep percolation from irrigation Note: Parameters listed in col 16-28

Card 5 is included only if IWTIR = 1.

CARD GROUP 2

Card 1 of 5

1- 6	X	-	Zip and region.
9-10	I	NTHB	Number of the beginning month of potential evapotranspiration calculations.

Column No.	Var type	Var name	Variable description
10-14	I	KPCF	Flag for computing et using crop curves from cards or polynomials in the CPCOEF subroutine. 0 = Read crop curves from cards 12 and 13. 1 = Compute crop curves from polynomials.
15-19	X	-	Columns used for additional indentification - farm no, field no, etc.
20-21	I	IDATA	Flag for computing irrigation schedules. 0 = Do not compute schedules. 1 = Compute schedules.
22-23	I	ICYCLE	Flag for reading another set of crop data (card 9) or reading climatic data (cards 1-8). 0 = Read card 1 and new year of clim data. 1 = Read card 1, NYR and IREAD only. Note: This prevents the inclusion of the rest of data in card 1. 2 = Read card 9 for another crop.
24-25	I	NCROP	Crop identification number: 1 = Small grain 2 = Beans 3 = Peas 4 = Potatoes 5 = Sugar beets 6 = Corn and sorghum 7 = Alfalfa 8 = Pasture Note: Weighted crop does not use a crop curve but requires a crop number to operate properly. Note: For weighted crop use any crop number (must be .GT. 0).
26-29	I	NDETB	Julian date (1-366) of planting or beginning of growing season.
30-33	I	NDETE	Julian date (1-366) of harvest or end of growing season.

Column No.	Var type	Var name	Variable description
34-37	I	NDCOV	Julian date (1-366) of effective crop cover date. Note: The Julian dates used should be for a leap year (366). The program uses a 366-day array but leaves out Feb 29 if the year is not a leap year. Dates for southern Idaho conditions are listed as follows (after Jensen, Wright, and Pratt; estimating soil moisture from climate, crop, and soil data; Transactions ASAE, Vol 14, No. 5, Sept-Oct, 1971, pp. 954-959, unpublished Appendix A, May 1971): Small grain — At heading Beans — Bloom or about 50 days after planting. Peas — Full bloom or 70 days after planting. Potatoes — About 80 days after planting. Sugar beets — About 110 days after planting. Corn or sorghum — About 10 days after tasseling on corn and heading for sorghum. Alfalfa — All season except 30 days after growth begins in the spring and 20 days after cuttings. Note: Cover data for alfalfa are not required, as they are taken care of internally in the program. Pasture — All season except 30 days after growth begins in the spring.
38-41	I	NCUTNG	Number of cuttings for alfalfa.
43-60	A	ICROP1	Eighteen spaces available for crop name.

Column No.	Var type	Var name	Variable description
61-66	A	IPLANT	Plant data in month/day nomenclature.
67-72	A	ICOVER	Cover date in month/day nomenclature.
73-78	A	IHARV	Harvest date in month/day nomenclature.
79-80	X	-	Card number.

Card 2 of 5

Column No.	Var type	Var name	Variable description
1- 8	X	-	Zip, region, and year.
9-12	I	NCUT	Julian date (1-366) of first cutting for alfalfa. Use this card only for alfalfa.
13-18	A	ICUT	First cutting date in month/day terms.

Subsequent NCUTS and ICUTS are entered on this card as I4, A6 up to a maximum of seven cuttings which ends in column 78.

Column No.	Var type	Var name	Variable description
79-80	X	-	Card number.

Card 3 of 5

Column No.	Var type	Var name	Variable description
1-20	X	-	Crop type and other identification.
21-75	R	RP	Crop coefficients from the Jensen-Haise crop curves at 10 percent intervals, starting at 0 and ending on 100 percent cover (a total of 11 values, 5 columns per coefficient).

Card 4 of 5

Column No.	Var type	Var name	Variable description
1-25	X	-	Crop type and other identification.
26-75	R	RD	Crop coefficients at 10-day intervals beginning with the 10th day after full cover and ending with 100th day (a total of 10 values, 5 columns per coefficient).

Note: Include cards 3 and 4 only if KPCF = 0 on card 1.

Column No.	Var type	Var name	Variable description
Card 5 of 5			
1-15	X	-	Zip, region, and other ID if desired.
16-20	I	IBGSEQ	Julian date (1-366) of soil thaw. Soil moisture budget computations are begun on this date.
21-25	I	IENSEQ	Julian date (1-366) of soil freeze. Soil moisture budget computations are stopped on this date.
26-30	I	JENDAY	Julian date (1-366) of last allowable date of irrigation in the season when properly specified allows a drying period prior to fall harvest.
31-35	R	AVAIL	Inches of available soil moisture in the root zone of the crop specified in card 1.
36-40	R	DSMBG	Depleted soil moisture of soil moisture budget computations. If ICARYO = 1 on card 1C only the DSMBG value for the first year will be used.
41-45	R	ADEPCT	Allowable depletion percentage. This is the percent of the available soil moisture which the crop is allowed to use before an irrigation is called for.
46-50	R	ADEPC1	Allowable depletion percentage for the first irrigation. Oftentimes this percent is less than ADEPCT because the root zone is not fully developed by the first irrigation.
51-55	R	FMEFF	Irrigation efficiency (in percent) for the type of system involved. Irrigation efficiency is defined as soil moisture added to the root zone divided by water delivered, expressed as a percent.

Column No.	Var type	Var name	Variable description
56-60	R	DRFTLS	Drift loss (in percent) if a sprinkler system is involved. This percent would include evaporation loss and is a percent of the water delivered to the field, not the water applied to the surface.
61-65	R	ROFLS	Runoff loss, in percent, of the water delivered to the field.
66-68	X		
69-70	A	IRRT	Irrigation type. GR - Gravity Sp - Sprinkler

Repeat cards 1-5 for each crop. Remember, that on the last 1 card in group 2, ICYCLE is set to 0 to begin reading card group 3 and climatic data.

CARD GROUP 3

Card 1 of 32

1- 6	X	-	Zip and region.
7- 8	I	NYR	Last two digits of the year. To terminate the job set NYR = 0 by using a blank card.
13-14	I	IREAD	Flag for reading climate data. 0,1 = Read only precipitation, temperature, and solar radiation, in that order. 2 = Read precipitation, evaporation, temperature, and solar radiation in that order. 3 = Read precipitation, relative humidity, evaporation, temperature, and solar radiation in that order. 4 = Read precipitation, wind, relative humidity, evaporation, temperature, and solar radiation in that order. 5 = Read only ETP (potential evapotranspiration) that has been computed previously and placed on cards.

Column No.	Var type	Var name	Variable description
			A minus sign - in front of any of the above IREAD numbers prevents the program from using any crop information. A minus sign is required for the first year of climatic data. For all the following years no minus is used.
15-18	I	NDB	Julian date of beginning climatic data.
19-22	I	NDE	Julian date of ending climatic data. If a full year data are processed, NDE should be 366. The program operates on a 366-day array and leaves out Feb 29 if the year is not a leap year.
23-30	R	ATERM	Average daily maximum temperature for the warmest month or the CT coefficient in the Jensen-Haise equation, ETP = CT*(T-TX)*RS. If the temperature is input, it must be preceded with a minus sign as a flag. The minus causes CT to be computed in subroutine JHCOEF.
31-38	R	BTERM	Average daily minimum temperature for the warmest month or the TX coefficient in the Jensen-Haise equation. A minus sign is not needed with this temperature input. See climatic summary of United States for ave daily max and min temps.
39-47	R	CONVRT	Conversion from gram-calories per square centimeter (Langleys) to inches of evaporation equivalent. CONVRT is used to convert solar radiation in Langleys to inches. CONVRT = 0.000673 if solar radiation is in Langleys. CONVRT = 1.0 if solar radiation is in inches.
48-59	R	SUMETP, SUMEVP	These variables are read in as zeros to start sums.

Column No.	Var type	Var name	Variable description
73-78	Z	OUT	This value read in as a blank for printing blanks in climatic data output.
79-80	X	-	Card number.

The following description applies to cards 2 through 32 which are climatic data - set up for 1 year on 31 cards - 1 card for each day of the month and 12 columns each representing a month for that particular day.

Card 2 of 32

1- 6	X	-	Zip code and region.
7- 8	X	-	Last two digits of the year.
9-10	I	NDAY	Day of the month (1-31).
11-15	X	-	Identification for data type:

Data type	Card No.
(Col 11-15)	(Col 79-80)
Prcp	2
Wind	3
Rel H or Dewpoint	4
Evap	5
Temp	6
RS (Solar)	7
ETP	8

16-20	R	DATA	Data for January corresponding to NDAY.
21-25	R	DATA	Data for February.
26-30	R	DATA	Data for March.
31-35	R	DATA	Data for April.
36-40	R	DATA	Data for May.
41-45	R	DATA	Data for June.

Column No.	Var type	Var name	Variable description
46-50	R	DATA	Data for July.
51-55	R	DATA	Data for August.
56-60	R	DATA	Data for September.
61-65	R	DATA	Data for October.
66-70	R	DATA	Data for November.
71-75	R	DATA	Data for December.
79-80	R	DATA	Card number.

Detailed information on data input is as follows:

Prcp	Precipitation in inches for the day - input as hundredths of an inch.
Wind	Wind in miles per day - no decimals.
Rel H	Relative humidity in percent - no decimals.
or Dewpoint	Dewpoint in degrees F.
Evap.	Pan evaporation in hundredths of an inch (comparative purposes).
Temp	Temperature input as maximum daily temperature in the first three columns of the five-column field, and as minimum daily temperature in the last two columns of the five-column field. For example:

Field XXXXX
Temp 9852
Maximum daily temp = 98
Minimum daily temp = 52

Average daily temperature may also be used. In the case where negative max or min temps are involved, the average temp must be used. (Note: A negative average may be used.)

Column No.	Var type	Var name	Variable description
RS			Solar radiation in Langleys or inches - see CONVRT on card 1. Langleys - no decimals, inches - hundredths.
ETP			Potential evapotranspiration computed externally and input for scheduling purposes.

The last data card is a blank card to exit the program - See NYR on card 1.

SECTION X

USER'S MANUAL - UNSATURATED FLOW PROGRAM

INTRODUCTION

This program is designed to simulate one-dimensional unsaturated flow between the ground surface and the water table. It includes the infiltration, redistribution, plant root extraction, and drainage of soil water under a growing crop. In particular, this program was developed as part of a water quality simulation model with the water contents and movement within the unsaturated zone as well as the deep percolation to the water table acting as input to other programs. A generalized diagram of the system modeled appears in Figure 12.

The program was originally written at the University of Arizona under a Bureau of Reclamation contract. The theoretical basis has been described in Dutt, et al. (5). However, a number of program improvements and modifications have been made including:

a. Improved restart ability, including use of tape, cards and printed output.

b. Addition of ability to simulate more than 1 year with a single run, including commencement of computations with a thaw date and stopping them on a freeze date.

c. Improved method of handling the upper boundary condition when there is no water at the surface and the zero flow condition prevails.

d. Addition of an option to compute the thaw date application when the profile is assumed at field capacity and multiple years are run.

e. Improved computation of the consumptive use to assure mass balance is maintained.

f. Consolidation of all references to a specific soil in program MØISTRE by calling a new subroutine named PRØP.

g. Development of a special form of PRØP in which a particular functional relationship is used. This permits soils properties for conductivity and diffusivity to be defined by card inputs, eliminating the need to modify the source deck.

h. Elimination of certain card groups when their options are not used.

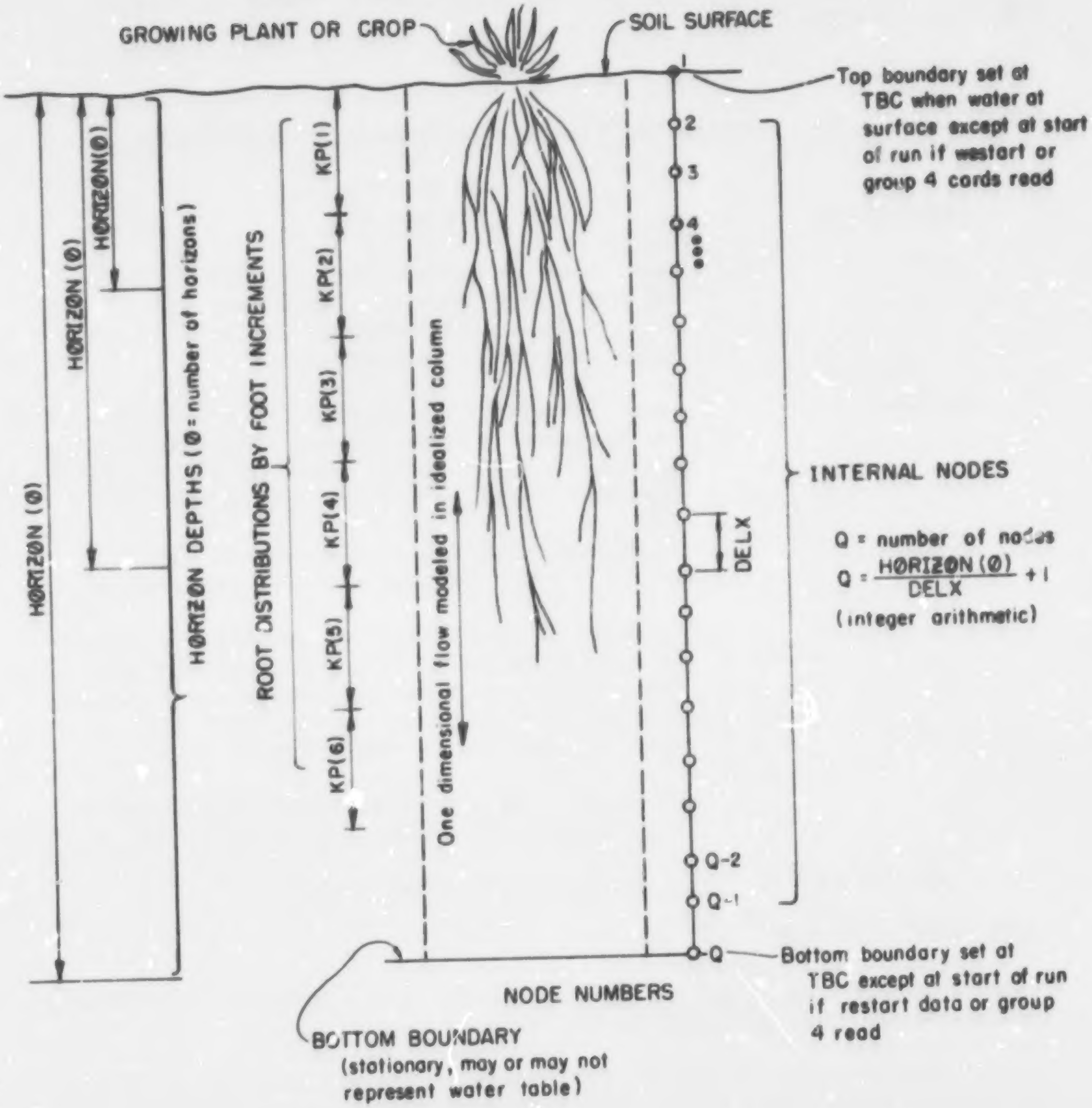

GROWING PLANT OR CROP
SOIL SURFACE
1
Top boundary set at TBC when water at surface except at start of run if restart or group 4 cards read
2
3
4
HØRIZØN (0)
HØRIZØN (0)
HØRIZØN(0)
HØRIZØN DEPTHS (0 = number of horizons)
ROOT DISTRIBUTIONS BY FOOT INCREMENTS
KP(1)
KP(2)
KP(3)
KP(4)
KP(5)
KP(6)
One dimensional flow modeled in idealized column
INTERNAL NODES
DELX
Q = number of nodes
$Q = \frac{HØRIZØN(0)}{DELX} + 1$
(integer arithmetic)
Q-2
Q-1
Q
Bottom boundary set at TBC except at start of run if restart data or group 4 read
NODE NUMBERS
BOTTOM BOUNDARY
(stationary, may or may not represent water table)

FIGURE 12. MODELED SYSTEM – UNSATURATED FLOW

i. Modification of input formats to pack more data on a single card.

This manual updates and replaces the user's manual found in Dutt, et al., (5), pp. 31-35.

UNIT NUMBERS

Five input-output devices or files are referenced by the program:

Unit designation	Unit description or purpose
INPUT	Card input is accomplished by READ statements without a unit number. The common input tape or unit (i.e., the computer system's standard input device) is understood.
ØUTPUT	Printed output is generated by PRINT statements without a unit number. The common output tape or unit (i.e., the computer system's standard output device) is understood.
PUNCH	Records are written to the punched card device of the computer by PUNCH statements.
5	The unit to which computed results are written on a saved magnetic tape. An entirely new tape may be generated or results can be added to a previously created tape. This tape is used as input to the interface program.
10	The unit to which restart data is written on a saved magnetic tape.

It is noted that tape 4 (5, p. 32) is no longer used.

DATA DECK STRUCTURE

There are eight basic groups of input cards in the data deck, as shown in Figure 13, and the variables are defined below.

Groups are numbered to conform with those of the original University of Arizona user's manual.(1) The consumptive use routine (CØNUSE) described in that publication does not correspond to the one in our program. An earlier version, in which the Blaney-Criddle constants and climatic data for two crops (barley and milo) are built into the program, is used. Group 5 inputs are not accepted.

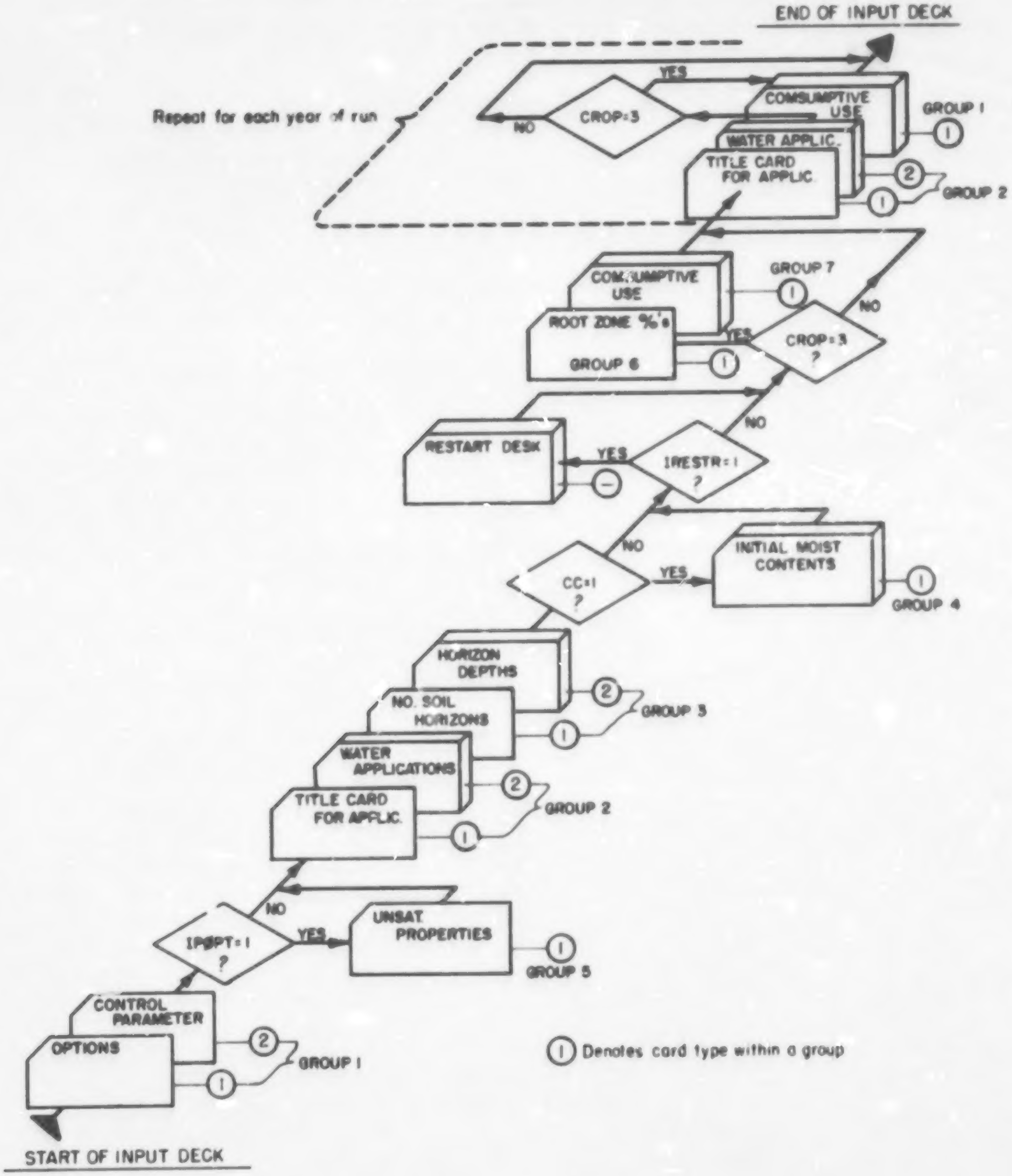

END OF INPUT DECK
Repeat for each year of run
YES
NO
CROP=3
COMSUMPTIVE USE
GROUP 1
1
WATER APPLIC.
TITLE CARD FOR APPLIC.
2
1
GROUP 2
COMSUMPTIVE USE
GROUP 7
1
NO
ROOT ZONE %'s
GROUP 6
1
YES
CROP=3 ?
RESTART DESK
YES
NO
IRESTR=1 ?
–
NO
INITIAL MOIST CONTENTS
YES
CC=1 ?
1
GROUP 4
HORIZON DEPTHS
2
NO. SOIL HORIZONS
1
GROUP 3
WATER APPLICATIONS
2
TITLE CARD FOR APPLIC.
1
GROUP 2
NO
IPØPT=1 ?
YES
UNSAT PROPERTIES
1
GROUP 5
CONTROL PARAMETER
2
OPTIONS
1
GROUP 1
1 Denotes card type within a group
START OF INPUT DECK

FIGURE 13. DATA DECK STRUCTURE UNSATURATED FLOW SUBMODEL

Group 8 has been added to allow input of soil properties when Campbell's method is employed to define diffusivity and conductivity relations. The restart deck does not have a group number, and is described separately in a later section.

CARD GROUP 1 - Input-Output Options and Run Conditions

Column No.	Var type	Var name	Variable description
Card 1 of 2			
1-5	I	IPUNCH	Option to allow restart data to be saved at the end of a run. If IPUNCH = 1, restart data are to be punched IPUNCH = 2, restart data are to be written on tape 10 IPUNCH = any other value, restart data are not saved
6-10	I	IRESTR	Option to allow restart data to be used as input for this run. If IRESTR = 1, restart data are read from cards IRESTR = 2, restart data are read from tape 10 IRESTR = any other value, restart data are not used
11-15	I	ISAVE	Flag to specify that a previously created output tape 5 is to be used. It is then necessary to position the tape to the correct position for the initial write, using INFIL5 and LLSTRT (below). If ISAVE = 1, use a previously saved tape 5.
16-20	I	ITENTH	Option to allow printed results to be outputed at 0.1-day intervals. If ITENTH = 1, print results every tenth day.

Column No.	Var type	Var name	Variable description
21-25	I	INFILS	Initial file number on tape 5 for the first write of output data (see RESTART OF PROBLEM).
26-30	I	LLSTRT	Julian day number of first day for which computations are made for the initial year of this run.
31-35	I	MMSTØP	Julian day number of last day in the last year (ISTØP) for which computations are made.
36-40	I	ISTØP	Stopping or ending year for this run.
41-45	I	IDEF	Option to select the deficit or depleted moisture method of determining the thaw date application. If IDEF = 1, use this option (see DEPLETED MOISTURE OPTION).
46-50	R	FCAP	Volumetric moisture content to be used as the field capacity value when the depleted moisture option (IDEF) is used. FCAP is expressed as a decimal (dimensionless).
51-55	I	IPØPT	Option to select the special form of subroutine PRØP to compute conductivities and diffusivities as a function of moisture content. If IPØPT = 1, then use this form (see UNSATURATED FLOW PROPERTIES). A Group 8 card must then be included.
Card 2 of 2			
1-5	I	AA	If AA = 1, print the initial input data.
6-10	I	BB	If BB = 1, print computed moisture contents on a daily basis.
11-15	I	CC	If CC = 1, read initial moisture contents from Group 4 cards.

Column No.	Var type	Var name	Variable description
16-20	I	LL	Julian day number of starting day in a full year (i.e., first day for all years except initial).
21-25	I	MM	Julian day number of starting day in a full year (i.e., last day for all years except IST0P).
26-30	R	BBC	Volumetric moisture content at the bottom boundary expressed as a decimal (dimensionless). If BBC = 1, then the bottom boundary is set at the TM value. BBC = 2, then the bottom boundary is set at the TS value. BBC = any other value, the bottom boundary is set at this value.
31-35	R	TBC	Volumetric moisture content at the top boundary expressed as a decimal (dimensionless). If TBC = 1, then the top boundary is set at the TM value. TBC = 2, then the top boundary is set at the TS value. TBC = any other value, the top boundary is set at this value.
36-40	I	YEAR	The year number corresponding to the initial year of this run.
41-45	I	CR0P	Crop selector used in computing consumptive use. If CR0P = 1, use the Blaney-Criddle formula with the constants in the program for barley. CR0P = 2, use the Blaney-Criddle formula with the constants in the program for milo. CR0P = 3, use consumptive use values read from cards in Group 7.

Column No.	Var type	Var name	Variable description
46-50	I	M	Minimum number of time intervals per day for applying the finite difference solution.
56-60	R	DELX	Distance between nodes for the finite difference solution (cm).
61-65	R	TS	Maximum (i.e., usually taken as the saturation value) moisture content expressed as a decimal (dimensionless).
66-70	R	TM	Arbitrary moisture content expressed as a decimal (dimensionless).
71-75	R	TD	Minimum (i.e., usually taken as permanent wilting point) moisture content expressed as a decimal (dimensionless). Consumptive use cannot be withdrawn by the sink term when this value is reached.
76-80	R	SM	Arbitrary initial moisture content for internal nodes (i.e., all nodes except top and bottom boundary) used when the CC and/or restart option are not used, expressed as a decimal (dimensionless).

CARD GROUP 2 - Water Applications

Card 1 of 2

1-5	I	IC0DE	A numeric code that can be used to identify the crop, climatic conditions, irrigation method, etc. It is merely displayed on output.
6-10	I	IYEAR	Year number identifying the year of inputs. It is merely displayed on output.
11-13	I	APPS	Number of water applications contained in the type 2 cards of this group for this year (maximum number is 50).

Column No.	Var type	Var name	Variable description
14-77	A	IDENT	Alphanumeric description to identify the water applications. It is merely displayed on output and may include information on the crop, climatic conditions, and irrigation methods.

Card 2 of 2

11-12	I	MON	Month of water application where January is 1, February is 2, etc.
13-14	I	IDAT	Date within month of water application.
15	A	ADENT	An alphanumeric identifier to denote the source of water, for example. I = irrigation, R or P = rainfall, S = snowmelt, etc. It is merely displayed on output.
16-20	R	AMT	Amount of application as a volume per unit area (inch^3/inch^2 or inch). Water is applied at the start of the day.

CARD GROUP 3 - Soil Identification and Depth

Card 1 of 2

1-2	I	O	Number of soil horizons.

Card 2 of 2

3-10	A	IDENT	Alphanumeric soil horizon identification which is merely displayed on output.
11-20	R	HORIZON	Depth from land surface to lower boundary of horizon (cm).

CARD GROUP 4 - Initial Moisture Contents

Card 1 of N

1-10 11-20 etc.	R	TO(I)	Initial volumetric soil moisture content of each depth node I including top and bottom boundary nodes expressed as a decimal (dimensionless). N is the number of nodes.

CARD GROUP 6 - Root Distribution

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10 11-20 etc.	R	KP(I)	Decimal fraction of roots located in the Ith foot of the soil profile (dimensionless). KP(1) is for the top foot, KP(2) is for the second foot, . . . KP(6) is for the sixth foot.

CARD GROUP 7 - Consumptive Use Values

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-5	I	ICØDE	A numeric code that can be used to identify the crop, climatic conditions, irrigation method, etc. It is merely displayed on output.
6-10	I	IYEAR	Year number identifying the year of inputs. It is merely displayed on output.
11-15 16-20 etc.	R	U(I)	Semimonthly consumptive use in the entire root zone for period I (acre-inches/acre or inches). I = 1 denotes January 1 through January 15, I = 2 denotes January 16 through January 31, etc. Thus, the first period in a month is from the 1st-15th, while the second is from the 16th to the end of the month.

CARD GROUP 8 - Unsaturated Flow Properties

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	KSAT	Saturated hydraulic conductivity (cm/day).
11-20	R	BEMP	Empirical constant b.
21-30	R	AIRENT	Air-entry potential (cm).

NODE SPACING

An idealization of the unsaturated flow system is shown in Figure 12. The horizon depths given by the group 3 cards, root zone distributions given by the group 6 card, and the nodal system are indicated. The number of nodes, Q, is based on the depth to the bottom of the deepest horizon, HORIZON (0), and the DELX value of card 2, group 1.

$$Q = \frac{\text{HORIZON}(0)}{\text{DELX}} + 1 \qquad [1]$$

The right hand expression is truncated because Q is integer. For example, if HORIZON(0) = 146. cm and DELX = 5.00 cm

$$Q = \frac{146.}{5.00} + 1 = 29.2+1 = 30.2 \rightarrow 30 \qquad [2]$$

If HORIZON(0) = 150. cm and DELX = 5.00 cm it follows that

$$Q = \frac{150.}{5.00} + 1 = 30. +1 = 31. \rightarrow 31 \qquad [3]$$

However, the internal representation of real numbers that are considered exact on input generally results in a stored value that is slightly different. Thus, in the previous example, the depth might be represented internally by a number slightly less than 150.0 cm. The number of nodes would then be computed as 30 which is a totally unexpected result.

In general, the use of any real numbers in an integer computation can produce unexpected results. Since it is necessary to know Q when initial conditions are read, it is recommended that the HORIZON(0) depth be adjusted to assure the desired number of nodes. In the previous example, this is accomplished by setting HORIZON(0) = 150. cm.

MOISTURE CONTENTS

The terms soil moisture content and soil moisture movement are used throughout this manual. More appropriately, the word "water" should be substituted for "moisture." Although a matter of semantics, the use of "water" is becoming more prevalent in literature.

Variables related to moisture contents include:

FCAP, card 1, group 1
BBC, TBC, TS, TD, SM, card 2, group 1
TO(I), group 4
similar variables in restart deck.

All contents are on a volumetric basis, defined as:

$$\theta = \frac{\text{volume of water in sample}}{\text{total volume of sample}} \qquad [4]$$

Laboratory data are usually expressed gravimetrically as:

$$\alpha = \frac{\text{weight of water in sample}}{\text{dry weight of soil in sample}} \qquad [5]$$

Both the volumetric and gravimetric moisture contents are dimensionless quantities. They are related by the equation:

$$\theta = \alpha BD/D_W \qquad [6]$$

where

BD = bulk density of the soil (F/L^3)*
D_W = density of water (F/L^3)

In the cgs system, the density of water is approximately 1 gm/cm^3. Expressing the bulk density in gm/cm^3 yields:

$$\theta = \alpha BD \quad \text{(numerically)} \qquad [7]$$

The program uses volumetric moisture contents for input and output. The above equations can be used to convert values. For example, if the percent moisture by weight is 30 percent and the bulk density is 1.5 gm/cm^3, then:

$$\theta = (0.30)\ (1.5) = 0.45 \qquad [8]$$

Since the bulk density of most soils is greater than 1, volumetric contents will always be higher than the corresponding gravimetric ones.

UNSATURATED FLOW PROPERTIES

The original program made use of statement functions and a series of IF tests in the main program (5, p. 31) to compute the conductivity and diffusivity. Since the IF tests appear in three places, making changes in the program for different soils was not only a nuisance but also an error prone process. To simplify program use and still retain sufficient flexibility, the statement functions were removed and the series of IF tests replaced by a single call to subroutine PRØP. The general form of the call is:

---

* Dimensional Units are denoted in parentheses where L denotes length, F denotes force, T denotes time, and - denotes a dimensionless quantity.

```
CALL PRØP (ZK, TD, K, D)
```

where: Z = volumetric moisture content at which the diffusivity is computed

ZK = volumetric moisture content at which the conductivity is computed

TD = volumetric moisture content below which the diffusivity and conductivity are assumed negligible and set to zero

K = conductivity at content ZK in cm/day (K is a real variable

D = Diffusivity at content Z in cm^2/day

The value of TD is obtained from the second card of group 1 and is normally taken as the wilting point. Although the conductivity and diffusivity are treated as constants during a time interval, they are evaluated at different moisture contents. For flow between two nodes, ZK is based on the average contents of the nodes at the start of the time interval. Z is based on extrapolation of results from the last two time levels for each of the nodes, averaged between them (5, equations [10], [11]). Under some conditions, it is possible for the program to compute Z or ZK values greater than the saturation value, TS on card 2 of group 1. Since TS is not passed to PRØP in the call list, provisions should be included to limit the value of Z and ZK to the saturated value when this occurs.

Subroutine PRØP can contain any degree of detail to approximate field data. Methods may vary from using tabular values to employing exponential forms (5, p. 31). A sample is given in the section entitled "Example of Subroutine PRØP."

The current form of MØISTRE does not pass information to subroutine PRØP specifying the depth or node number at which the properties are computed. This is due to the fact that only homogeneous soils are allowed. Original intentions were to allow for layered soils, hence the structure of the group 3 cards. (As noted in 5, footnote A, Table 23, p.33):

> "Soil 'horizons' referred to in this context do not correspond to morphological soil horizons. Program MØISTRE

> models moisture movement in uniform soils only, so soil 'horizons' as referred to here have no function except to correspond to the 'chemistry horizons' in the Biological-Chemical Program for convenience."

The horizon references have been left in the program for future expansion to handle variable flow properties. This would require the addition of the node number in the call list of PRØP. Properties could then be related to a particular horizon.

A special form of PRØP has been developed for use with a specific form of the moisture-release curve, as outlined by Campbell (23). This method is purported to be as good as the Millington-Quirk method (9) which is presently finding wide use and acceptance. This routine receives some data through a CØMMØN block. The method is detailed and is outlined as follows:

a. Plot moisture-release data on log-log paper.

b. If a straight line fits the plotted data reasonably well, then the moisture-release curve is approximated by an exponential form and the method of Campbell can be used.

c. Evaluate the slope of the line to obtain BEMP and the air-entry potential AIRENT.

d. Select the option by setting IPØPT=1 on the first card of group 1.

e. Include the group 8 card on input.

INITIAL BOUNDARY CONDITIONS

The top and bottom boundary conditions are established by variables on card 2 of group 1. Values are set as follows:

a. Top boundary (TBC) -

if TBC = 1,	set TBC = TM
if TBC = 2,	set TBC = TS
if TBC = any other value,	use TBC as read

b. Bottom boundary (BBC) -

if BBC = 1,	set BBC = TM
if BBC = 2,	set BBC = TS
if BBC = any other value,	use BBC as read

When initial conditions are not read from the group 4 cards or restart data from cards or tape, all nodes other than the boundary nodes (i.e., internal nodes) are initialized to SM. Should either the group 4 cards (CC=1) or restart data (IRESTR=1 or 2) be read, values must be included for both boundaries. These override the TBC and BBC values at the start of the first time step. When computations are finished for this step, the top boundary condition depends on the availability of water at the surface for infiltration while the bottom boundary condition reverts to the BBC value (see MASS BALANCE). If water does remain at the surface, the top boundary is set at TBC.

Logically, the group 4 input option (CC=1) and restart options (IRESTR=1 or 2) are not used for the same run. However, if they are, the initial moisture contents read from the restart data override those from the group 4 cards.

CONSUMPTIVE USE VALUES

Values read from the group 7 cards (CRØP=3) are the total consumptive use values for each semimonthly period. The first period for a given month extends from the 1st through the 15th while the second extends from the 16th to the last day of the particular month. Consumptive use is withdrawn at a uniform rate equal to the total divided by the number of days in the given semimonthly period.

If the starting date of the run is not the 1st or the 16th, it is necessary to adjust the input values to obtain the correct withdrawal. Thus, if:

U = total required consumptive use for period (acre-inches/acre)
N = number of days in full period
A = actual number of days in period based on starting date
$\overline{U}$ = adjusted or input consumptive use (acre-inches/acre)

$$\overline{U} = \frac{UN}{A} \qquad [9]$$

For example, if the total consumptive use to be removed is 1.00 inch and the starting date is July 13, then:

$$\overline{U} = \frac{(1.00 \text{ inch})\ (15)}{(3)} = 5.00 \text{ inches} \qquad [10]$$

It is seen that the above equation merely converts the total consumptive use to the required withdrawal rate (U/D) and then computes the input value by using the total number of days in the period. The same approach is employed when the ending date of the run does not fall on the 15th or the last day in the month.

DEPLETED MOISTURE OPTION

A special option is available to handle winter precipitation for areas experiencing an annual freeze-thaw cycle. It is selected by setting IDEF=1 on the first card of group 1. The method is based on the assumption that the entire profile is at least at a moisture content, FCAP, normally considered to be the field capacity.

The starting day for a full year is considered as the thaw date while the terminating day is the freeze date. No further infiltration or redistribution of moisture occurs after the freeze date until the thaw date of the next year. Winter precipitation during the period is assumed sufficient to raise the moisture level throughout the profile to the FCAP value. Any excess is presumed to melt and run off or to evaporate.

The required quantity of water to raise the moisture content at each node to FCAP is accumulated on the freeze date. If a node is already higher, there is no reduction in the total. This total is printed on output and used as the first application for the next year.

Water application data for the succeeding year must include the depleted moisture as the first application. The total number of applications (APPS) must include it and the date and month specified for it. The amount should be left blank. Although the application date normally coincides with the thaw date, this is not necessary.

The depleted moisture option does not function until the end of the first year's computations. Consequently, if the same technique is employed for the starting year, the application must be computed and included on the group 2 card. Similarly, restart data do not include the quantity of depleted moisture from the previous year.

The following message is printed at the end of each year's computations when the depleted moisture option is used:

```
MOISTURE DEPLETED FOR YEAR = yy, MONTH = mm, DATE = dd (DAY NUMBER
  = jj) IS = ii INCHES
```

where: yy = year number of run
mm = month number with mm=1 for January, mm=2 for February, etc.
dd = date within month
jj = Julian day number
ii = depleted moisture in the entire column in inches at the end of the given date

yy, mm, and dd as well as jj correspond to the last day in a full year or the stopping day of the run for the last year run.

STARTING AND STOPPING DATES

Changes have been made to the program to allow runs beyond 1 year, thus removing the limitations noted in Dutt, et al. (5, p. 35). All dates are Julian with a perpetual calendar assumed (no leap years).

The starting year number of the run is given as YEAR (card type 2, group 1) while the ending year is ISTØP (card 1, group 1). These years may be integer numbers starting with 1, 2, etc., or actual years such as 1975, 1980, etc. Checks are made at the finish of each year's computations to determine if the run is complete. Consequently, at least a single year is run, even if ISTØP is less than YEAR. In general, the number of years in the run is (YEAR-ISTØP+1).

The first year's computations commence with the Julian date LLSTRT (card 1, group 1) and end with MM (card 2, group 1) unless YEAR = ISTØP. In this case the last day of computations is MMSTØP (card type 1, group 1). Subsequent years commence with date LL (card 2, group 1) and end with day MM unless the last year (ISTØP) is being processed in which case the ending date is MMSTØP.

As an example, if computations are desired to commence on July 12, 1975, and to end on November 14, 1977, with a thaw date of May 12 and freeze date of November 27, the following values are used:

YEAR = 1975 ISTØP = 1977
LLSTRT = 193 (i.e., July 12) MMSTØP = 318 (i.e., Nov. 14)
LL = 132 (i.e., May 12) MM = 331 (i.e., Nov. 27)

The starting and ending dates for each year of the run are:

Year	Starting date	Ending date
1975	193	331
1976	132	331
1977	132	318

If there is no freeze-thaw cycle, then LL=1 (Jan. 1) and MM=365 (Dec. 31). Other variables are used in the manner outlined above.

DEFICIT MOISTURE

During a given time step, the program compares the quantity of water specified for removal by the plants at a given node to the available moisture. The available moisture is taken as the difference between the moisture content at the start of the period and the input minimum level, TD, usually taken as the permanent wilting point. Should the consumptive use exceed the available water, the difference is computed and saved as the deficit moisture, and the consumptive use actually removed is reduced to the available water. This technique ignores the possibility of water moving from adjacent nodes during the time step. Since contents are very low resulting in low transmission rates, this appears to be a logical approach.

Should moisture levels rise above the minimum at later times, the program again attempts to remove the specified consumptive use.

The method outlined above is obviously a simple approach to a complex problem. The availability of water to a plant depends on soil moisture levels, salinity conditions in the soil profile, crop type, present health of the plants, stage of plant development, as well as the physical soil properties. In addition, the relationship of the entire root system to required water needs of the plant is involved.

When printed output is obtained at tenth-day intervals, a deficit moisture condition results in the message:

```
DEFICIT MOISTURE SITUATION ENCOUNTERED nn TIMES THIS TENTH DAY.
AMOUNT IS aa CM
```

Where: nn is the number of individual situations that a moisture deficit was encountered
aa is the accumulative deficit in cm^3/cm^2 or cm

A similar message appears with the daily output, except values correspond to totals for the day and the message reads . . . TIMES THIS DAY . . . instead of . . . TIMES THIS TENTH DAY . . . .

The cumulative deficit since the start of the run is DEFAMC which is routinely printed on output, even if it is zero. It is also included in the restart deck as is the cumulative deficit at a given node, Z(J), since the start of the run.

MASS BALANCE

A mass balance check is included to assure program integrity and to provide a means of assessing the adequacy of the time steps being used in the simulation. The entire soil column is considered and an accounting made of all inputs and outputs of water. Results of the check appear with the printed output. The individual components are carried forward in the restart data.

The usual conservation of mass equation:

$$\text{mass in} - \text{mass out} = \text{change in mass storage} \qquad [11]$$

is applied to the soil column. The only water entering the column is from infiltration of precipitation and irrigation water. Water leaves the system as consumptive use and as deep percolation (leachate) across the water table.

Defining:

ETS = cumulative infiltration (water percolating through the surface into the column).

ET = cumulative plant evapotranspiration actually removed.

CL = cumulative water leached through the bottom of the column (deep percolation). A positive value denotes water leaving the column and a negative value denotes water moving into the column from below the water table.

DIF = change in storage of water in the soil column since start of run (final quantity less the initial quantity).

The units of the variables on output are in cm^3 of water per cm^2 of surface area or simply cm.

The mass balance equation becomes:

$$ETS - CL - ET = DIF \qquad [12]$$

from which:

$$CL = ETS - ET - DIF \qquad [13]$$

Letting:

$$CHECK = ETS - ET - DIF \qquad [14]$$

$$CL = CHECK \qquad [15]$$

Printed output includes CL, CHECK, ETS, ET, and DIF. The CL and CHECK values should compare reasonably well. Values for DIF and, consequently, CHECK are only updated at the end of each day. Therefore when 0.1-day output is selected, the mass balance check is only correct at the end of each day.

The ET value is the quantity of water actually removed by the program. An adjustment procedure is included to assure that this value equals that on input when there are no deficits. This procedure is based on the node spacing, root distribution with depth, and the program method for computing the withdrawal at each node. When low-moisture levels occur and a deficit moisture (DEFAMC) results, the total consumptive use on input should equal DEFAMC + ET. The mass balance equation is unaffected.

A factor related to the mass balance computations is the approximate manner of treating the upper boundary. When water remains at the surface, the moisture content of the upper boundary is TBC. Once all the water infiltrates, an extrapolation procedure is used to estimate the top boundary moisture content for the next time step. There is no assurance that the zero flow condition (i.e., a specified gradient) is satisfied. Consequently, it is found that the program computes water crossing the surface (in both directions) at later times.

The ETS value is the total quantity of water crossing the surface and is computed on the basis of gradients and soil properties as are all flows. The quantity of water at the surface is stored in an accumulator called HED which also appears in the restart data. When HED is less than or equal to zero, all the water has infiltrated. However, if additional water is computed as entering the column, it reduces HED further (i.e., HED becomes more negative) and is included in both ETS and a value called CI. Consequently, CI includes the net infiltration when water is at the surface plus any infiltration resulting from errors in handling the upper boundary.

When there is no water at the surface and a quantity of water is computed as leaving the column, flowing upward across the surface, it is stored in a separate accumulator called CNA. It does not alter the value of HED or CI, but will reduce ETS. The cumulative value of CNA for the run is CNI.

From the above description:

$$\mathrm{ETS} = \mathrm{CI} - \mathrm{CNI} \qquad [16]$$

It is emphasized that the CNA value represents the quantity of water moving upward since all of the surface water from the last application infiltrated the column. It is a result of the approximate treatment of the upper boundary and as such is an error. The corresponding error due to downward movement is the HED which increases negatively until the next water application. When the application date is reached, the program applies:

$$\mathrm{HED} + \mathrm{CNA} + \mathrm{AMT(I)} \qquad [17]$$

HED and CNA tend to compensate. Together they represent the error produced in handling the upper boundary which alters the application specified on input. After the last application is made for a given year, the program checks the value of CNA. If it is appreciable, (CNA greater than 0.05 cm), an application of HED + CNA is applied the next day. This assures the value of ETS compares closely with the accumulated AMT(I) specified on input. It is noted that units on CNA, CNI, CI, and HED are all in cm^3 of water per cm^2 of area or simply cm on the printed output.

RESTART OF PROBLEM

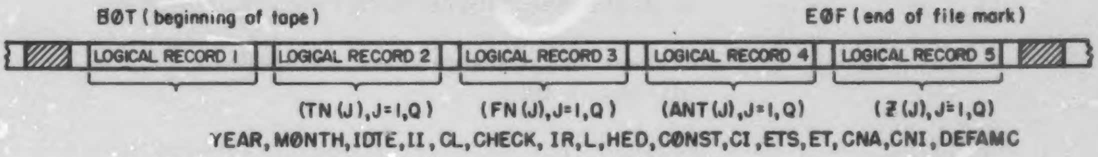
A problem may be run in successive stages using the restart capability. Data necessary to restart a problem are automatically printed during the run and may also be punched on cards or written to magnetic tape (or disc storage) at the end of the run. The data can be used in a subsequent run to continue the problem solution.

Restart data are directed to a permanent storage medium using the IPUNCH option (card 1, group 1). If:

IPUNCH = 1 data are punched on cards
IPUNCH = 2 data are written to unit 10 which may be equipped to a magnetic tape or to permanent disc storage
IPUNCH = any other value, no restart data are placed on a permanent storage medium

Organizational structure on unit 10 and deck structure for the punch file are shown in Figure 14. Tape 10 is unformatted (binary) while the punch cards are formatted as indicated in Figure 14. The variables are defined below.

YEAR, MØNTH, IDTE	The year, month, and date corresponding to the time for which the restart data were written. Month = 1 for January, 2 for February, etc.
II	The Julian day number corresponding to MØNTH and IDTE.
IR	Maximum rate of soil water movement between nodes. It is used internally by the program to select the time increment for solving the finite difference equations (cm/day).
L	Number of next irrigation or precipitation event.


B0T (beginning of tape)
E0F (end of file mark)
LOGICAL RECORD 1
LOGICAL RECORD 2
LOGICAL RECORD 3
LOGICAL RECORD 4
LOGICAL RECORD 5
(TN (J), J=1,Q)
(FN (J), J=1,Q)
(ANT (J), J=1,Q)
(Z (J), J=1,Q)
YEAR, M0NTH, IDTE, II, CL, CHECK, IR, L, HED, C0NST, CI, ETS, ET, CNA, CNI, DEFAMC

TAPE 10 RESTART DATA

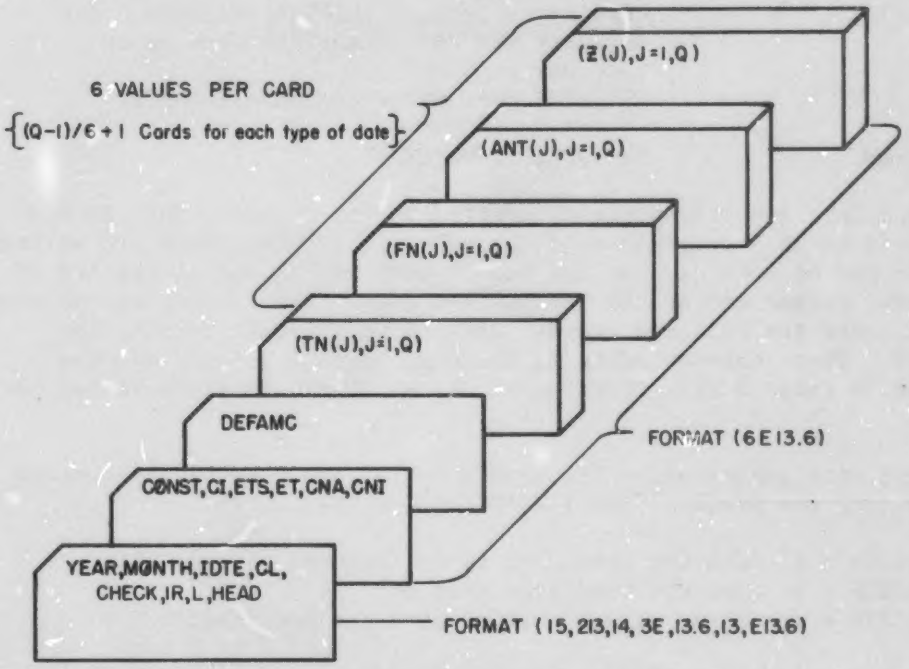

(Z(J), J=1,Q)
6 VALUES PER CARD
{(Q-1)/6+1 Cards for each type of date}
(ANT(J), J=1,Q)
(FN(J), J=1,Q)
(TN(J), J=1,Q)
DEFAMC
FORMAT (6E13.6)
C0NST, CI, ETS, ET, CNA, CNI
YEAR, M0NTH, IDTE, CL,
CHECK, IR, L, HEAD
FORMAT (15, 213, 14, 3E, 13.6, 13, E13.6)

FIGURE 14. PUNCHED CARD RESTART DECK-UNSATURATED FLOW SUBMODEL
(RESTART DATA)

CØNST	Initial quantity of water in the unsaturated soil column (cm^3 of water per cm^2 of surface area or cm).
Q	Number of nodes in the unsaturated column used to solve the finite difference equations.
TN(J)	Present moisture content at node J (dimensionless).
FN(J)	Present rate of water movement between nodes J and J + 1 (i.e., between node J and the next one below it) (cm/day).
ANT(J)	Anticipated moisture content for the next time step to be used in evaluating the diffusivity at node J (dimensionless) (see UNSATURATED FLOW PROPERTIES).
Z(J)	Cumulative deficit moisture at node J (cm^3 of water per cm^2 of surface area or cm).

CL, CHECK, HED, CI, ETS, ET, CNA, CNI - See MASS BALANCE.

DEFAMC	See DEFICIT MOISTURE

Restart data are automatically written to the common output device (printed output) regardless of the value of IPUNCH. Data are written at the end of 15th day, at the end of each month, and at the end of the run, regardless of the termination date. This output may be used to generate the required restart deck if an abnormal termination occurs. Items corresponding to those in logical records 2-5 are listed in nodal order, starting at the surface with seven values per line.

Restart data generated by the IPUNCH option are used by the program by setting the restart flag IRESTR appropriately. If:

IRESTR = 1 data are read from cards (Figures 13 and 14)
IRESTR = 2 data are read from unit 10
IRESTR = any other value, restart data are not used.

Restart data are intended to be used for the day following the date on which it was written. The program does not check dates although they do appear with the printed input data.

When a problem is restarted and tape 5 output is saved, it is necessary to position tape 5 correctly (see OUTPUT).

When restart data are read, the CC=1 option should not be used. However, if it is, moisture contents from the group 4 cards will be overridden by the restart data (see INITIAL AND BOUNDARY CONDITIONS). Run information and options (group 1), water applications (group 2), horizon data (group 3) as well as root zone data (group 6), consumptive use values (group 7), and unsaturated flow properties (group 8) when used must be included. Starting and ending dates as well as water applications for the entire year must be included, corresponding to the year in which the restart data were developed.

LIMITATIONS

The program has been developed with the following restrictions:

a. Only homogeneous soils are allowed. The extension to layered conditions would be relatively simple (see UNSATURATED FLOW PROPERTIES).

b. The bottom boundary is at a fixed location. The fluctuating water table is not treated.

c. A single, constant root pattern is used.

Problem size is restricted by allocated storage to:

a. maximum number of nodes = 60

b. maximum number of water applications = 50

c. maximum number of horizons = 9

There is no limit on the number of years run.

Use of the CRØP = 1 or 2 option is not recommended since the Blaney-Criddle coefficients are for two crops based on Arizona data (see DATA DECK STRUCTURE).

OUTPUT

Program output consists of printed listings, punched cards, and both computed results and restart data written to magnetic tape (or disc storage).

a. Printed data are listed by the program on the file called ØUTPUT. It includes both standard and optional output.

(1) Standard output includes:

(a) Input data: unsaturated flow properties when Campbell's method is used, water application dates and amounts, evapotranspiration values, and restart data read from tape or cards when the run is restarted.

(b) Computed results: the amount of water applied on a given date; mass balance results, upper boundary information, deficit moisture values and the number of time increments used for a given day for each day of the run; and restart data at the end of the 15th, the month, and the run.

(2) Optional printed output includes:

(a) Input data: control and run parameters, initial moisture contents, soil horizon data, and root distributions if AA = 1 on card 2, group 1.

(b) Computed results: moisture contents on a daily basis if BB = 1 on card 2, group 1; mass balance results, upper boundary information, deficit moisture values, the number of time increments used thus far for the day, and moisture contents at 0.1-day intervals if ITENTH = 1 on card 1, group 1.

(3) Special printed messages include:

(a) Depleted moisture message at the end of each year and at the end of the run when IDEF = 1 on card 1, group 1 (see DEPLETED MOISTURE OPTION).

(b) Deficit moisture message whenever a deficit is encountered during a given day (see DEFICIT MOISTURE).

(c) Unstable solution message whenever this situation is encountered (see HINTS ON USE).

(d) Error messages regarding tape 5 when a saved tape is used (ISAVE = 1 on the group 1 card) and the error condition is detected (see discussion below on tape 5 output).

The deficit moisture and unstable solution messages are given at the end of each 0.1 day when ITENTH = 1 and the given situation occurs.

b. Restart data are included in the printed output and may be written to unit 10 or to the punch file (see RESTART OF PROBLEM).

c. Computed results are written by the program on unit 5 as standard output at the end of each 0.1 day. Data are written without format in binary form by the single write statement:

```
WRITE (5)  YEAR, II, XT, CI, CL, HED, ETS, DEFAMC, (J, TN(J),
           Z(J), SF(J), U(J), J=1, Q)
```

Where: YEAR = current year number
II = Julian day number
XT = time within the day corresponding to the written data (i.e., 0.1 day, 0.2 day, . . . 1.0 day)
CI, CL, HED, ETS - See MASS BALANCE
J = node number (see NODE SPACING)
TN(J) = volumetric moisture content at time XT for node J (cm^3/cm^3 or -)
Z(J) = deficit moisture at node J during the last 0.1-day interval (cm^3 of water/cm^2 of surface area or cm)
SF(J) = total soil moisture flux (i.e., total quantity of water moving) between node J and (J+1) during the last 0.1 day (cm^3 of water/cm^2 of surface area or cm)
U(J) = evapotranspiration rate for node J based on the input data (cm^3 of water/cm^2 of surface area/day or cm/day)

An end-of-file mark is written at the end of each year's data. Consequently, each year's data can be considered a single logical file. When a problem is restarted and a saved tape 5 is to be written to, it is necessary to position it for the initial write.

Use of a saved tape is indicated by setting ISAVE=1 on the group 1 card. The initial file to which additional computed results are to be added is denoted as INFIL5 on the group 1 card. The program skips over the first (INFIL5-1) files, positioning tape 5 to the first record in INFIL5. If the starting date LLSTRT equals LL (the first day in a full year), the tape is assumed positioned and ready to go (i.e., INFIL5 is empty). If LLSTRT is not equal to LL, 10 records per day are read, the date read is checked against (LLSTRT-1), with the process stopping when it is found. The next write will then generate data for the first 0.1-day interval in day LLSTRT.

Two abnormal situations can occur during the process, resulting in error messages and program termination:

a. The end-of-file is reached before day number (LLSTRT-1) is reached. Restarting at LLSTRT would leave a gap in the records in INFIL5. This situation includes the case of an empty file. The following message is printed:

```
END FILE FOUND ON TAPE 5 BEFORE DAY NO. LLSTRT-1 FOUND,
EXECUTION TERMINATED
```

b. The first day number read from the file may exceed LLSTRT. It is then impossible to position tape 5 correctly. The following message is printed:

```
DAY READ FROM TAPE 5 EQUALS OR IS GREATER THAN STARTING
DAY, EXECUTION TERMINATED
```

Tape 5 is intended to be used as input to an interface program which interfaces the unsaturated flow program with an unsaturated chemistry and a drainout program.

HINTS ON USE

The following items are intended to guide the user in the intelligent use of the program. Some of the items are discussed elsewhere in the user's manual but are noted here for ready reference.

Selection of Maximum Time Step

Mass balance errors generally increase as the average time step for solving the finite difference equations increases. This is due to errors inherent in using finite differences as well as those resulting from the techniques that are used to handle the nonlinear soil properties.

Minimum computer costs dictate as large a time step as practical. The time step is automatically reduced when water is applied. This reduction is required because moisture conditions and, consequently, the unsaturated flow properties are rapidly changing with time. The reduced step is 0.001 day corresponding to 1,000 steps per day. These steps are gradually increased as the maximum rate of moisture movement in the profile decreases. The user limits the maximum size to M steps per day on card 2, group 1.

Since results are written to tape 5 on a 0.1-day basis, the largest time step is logically 0.1 day (M=10). However, the program checks the size of the step it is about to use and reduces it, if necessary, to obtain computed results at the 0.1-day interval.

Because of this, situations can occur in which successive time steps exhibit large variations in size. For example, steps of 0.045, 0.050, and 0.005 might result from specifying M=20. Experience has shown that better results are obtained when the tenth-day period is divided into more nearly equal steps, e.g., 0.035, 0.035, and 0.030. This is due to the method of handling the upper boundary and of estimating the anticipated moisture content used in evaluating the diffusivity (5, equations [10], [11], p. 7).

For most soils, a value of M=30 is recommended. The actual number of time steps used is given as NSTEPS in the printed output. Both mass balance results and conditions at the upper boundary should be used in selecting the appropriate value of M.

Unstable Solution

Because of the methods used to deal with the nonlinear flow properties, the approximate treatment of the upper boundary, and numerical solution errors, the computed moisture contents may exceed the physical bounds. When the computed value is less than zero or greater than saturation (i.e., TS) at a node for one time step, a counter is incremented. The total number of such occurrences is noted in the printed output for each 0.1 day when ITENTH=1 and for each day. The printed message is:

> UNSTABLE SOLUTION SITUATION ENCOUNTERED nn TIMES THIS TENTH DAY or (. . . THIS DAY)

Normally, this situation only occurs on application dates when the soil profile is very dry and the amount of applied water large. Moisture contents then exceed TS. Under rare conditions, moisture levels may fall below zero, especially when the wilting point, TD, is very near zero. In either case, if the count is low and computed contents exceed the limits only slightly (say 0.01 or less), the situation is not serious and can be ignored. Generally, major difficulties result only when very heavy soils (low conductivity) are encountered. In this case, improvement can be made by increasing the number of nodes used to simulate the soil column.

Adequacy of Unsaturated Flow Properties

The unsaturated flow properties should be evaluated by performing several simulations to duplicate soil properties commonly used by soil scientists. These include field capacity, specific yield, wilting point, and water holding capacity.

Uniform Initial Conditions

Whenever uniform initial conditions are desired, the value of CC on the type 2, group 1 card should be left blank or set to zero. The

SM value on the same card is then used for initial conditions at all internal nodes.

Deficit Moisture

Whenever the deficit moisture situation is encountered, the reason for it should be determined. Normal irrigation practices attempt to prevent such conditions. Items that should be considered include the unsaturated flow properties, consumptive use rates, and the irrigation schedules.

Boundary Conditions

The top and bottom boundary conditions need not be set at saturation. The top boundary condition, used when water is at the surface, can be reduced to account for surface resistance due to compaction, inwashing, swelling of colloids, and the breakdown of soil structure. The bottom boundary may not represent a water table. Consequently, any moisture condition can be used to model it, corresponding to the desired tension.

EXAMPLE OF SUBROUTINE PRØP

Introduction

When the method of Campbell is not used to compute the unsaturated flow properties, the user must supply his own property subroutine PRØP. The general form of the call is:

```
CALL PRØP (Ƶ, ƵK, TD, K, D)
```

where: Ƶ = volumetric moisture content at which the diffusivity is computed

ƵK = volumetric moisture content at which the conductivity is computed

TD = volumetric moisture content below which the diffusivity and conductivity are assumed negligible and set to zero

K = hydraulic conductivity at content ƵK in cm/day (a real variable)

D = diffusivity at content Ƶ in cm^2/day

Subroutine PRØP may use any method to determine the conductivity and diffusivity. Tabular values with an interpolation function or mathematical relationships may be used. Particularly convenient mathematical relations are those based on exponential forms.

Exponential Forms: Semilog

Consider the case where data plotted on semilog paper can be represented by a straight line as shown in Figure 15. Points 1 and 2 are arbitrary points on the straight line while r is a reference point at which the unsaturated flow property is P_r. The equation of the straight line is:

$$\log P = \log P_r + \text{slope} \times (\theta-\theta_r) \qquad [18]$$

The slope is given by:

$$\text{slope} = \frac{\log P_2 - \log P_1}{(\theta_2-\theta_1)} \quad \frac{\log (P_2/P_1)}{(\theta_2-\theta_1)} \qquad [19]$$

Equation [18] becomes:

$$\log P = \log P_r + \frac{\log (P_2/P_1)}{(\theta_2-\theta_1)} \; (\theta-\theta_r) \qquad [20]$$

The conversion from base 10 to base e logarithms is:

$$\log_{10} x = 0.43429 \ln x \quad \text{or} \quad \ln x = 2.303 \log_{10} x$$

Consequently, equation [20] becomes:

$$\ln \left(\frac{P}{P_r}\right) = 2.303 \, \frac{\log (P_2/P_1)}{(\theta_2-\theta_1)} \, (\theta-\theta_r) \qquad [21]$$

The logarithmic function $x=\log_b y$ is defined as the inverse of the exponential function and is given by the relationship $y=b^x$ where b is the base. Thus for natural logarithms $b=e$, $x=\ln y$, and $y=e^x$. Consequently, equation [21] becomes:

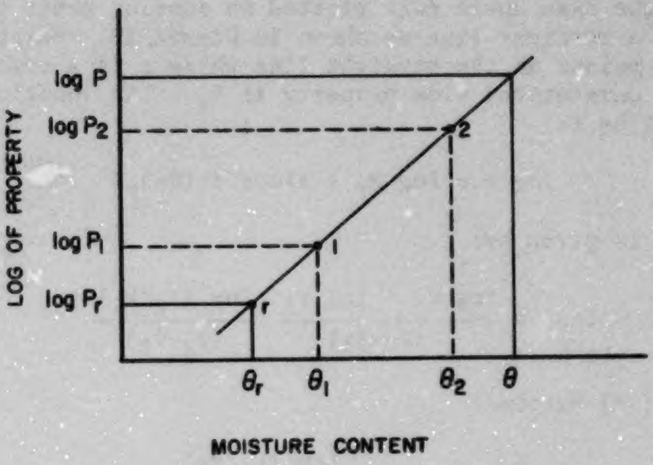
$$p=p_r \, e^{\frac{[2.303 \log (P_2/P_1)}{(\theta_2-\theta_1)} \quad (\theta-\theta_r)]} \qquad [22]$$

The exponent of e can be written as:

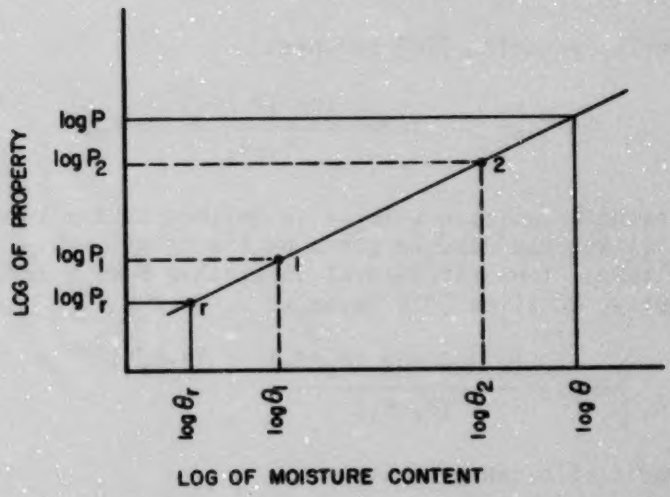
$$E = C \; (\theta-\theta_r) \qquad [23]$$

where:

$$C = 2.303 \, \frac{\log (P_2/P_1)}{(\theta_2-\theta_1)} \qquad [24]$$


log P
log P_2
log P_1
log P_r
LOG OF PROPERTY
2
1
r
θ_r
θ_1
θ_2
θ
MOISTURE CONTENT

(a) STRAIGHT LINE ON SEMI-LOG


log P
log P_2
log P_1
log P_r
LOG OF PROPERTY
2
1
r
log θ_r
log θ_1
log θ_2
log θ
LOG OF MOISTURE CONTENT

(b) STRAIGHT LINE ON LOG-LOG

FIGURE 15. UNSATURATED FLOW PROPERTIES-EXPONENTIAL FORMS

C is a constant (essentially the slope) which is evaluated by selecting two points 1 and 2 so that $\theta_2 > \theta_1$ and obtaining the θ's and corresponding P values. In addition, a reference point is selected (which could coincide with either point 1 or 2 if desired) and the values of θ_r and P_r obtained.

Exponential Forms: Log-log

Consider the case where data plotted on log-log paper can be represented by a straight line. The equation of the straight line is:

$$\ln \frac{(P)}{P_r} = 2.303 \frac{\log (P_2/P_1)}{\log (\theta_2/\theta_1)} \log (\theta/\theta_r) \qquad [25]$$

$$p = p_r \, e^{\left[2.303 \frac{\log (P_2/P_1)}{\log (\theta_2/\theta_1)} \log (\theta/\theta_r)\right]} \qquad [26]$$

The exponent of e can be written as:

$$E = C \log (\theta/\theta_r) \qquad [27]$$

where:

$$C = 2.303 \frac{\log (P_2/P_1)}{\log (\theta_2/\theta_1)} \qquad [28]$$

C is evaluated in a similar fashion to that for the semilog form.

Example

The log-log form is often preferable to the semilog form as it usually results in a better straight line fit. Several straight line segments may be required to approximate actual data, regardless of the form. The following example illustrates use of the semilog form with several straight line segments.

Measured data defining the moisture-release curve (h vs. θ) and the conductivity (K vs. θ) are plotted as points on the semilog plot of Figure 16. Possible functional relations are shown by the solid curves. Diffusivity values were computed by selecting a given θ, determining $K(\theta)$, evaluating the slope of the moisture-release curve, and applying the relationship:

$$D(\theta) = K(\theta) \frac{\partial h}{\partial \theta} \qquad [29]$$

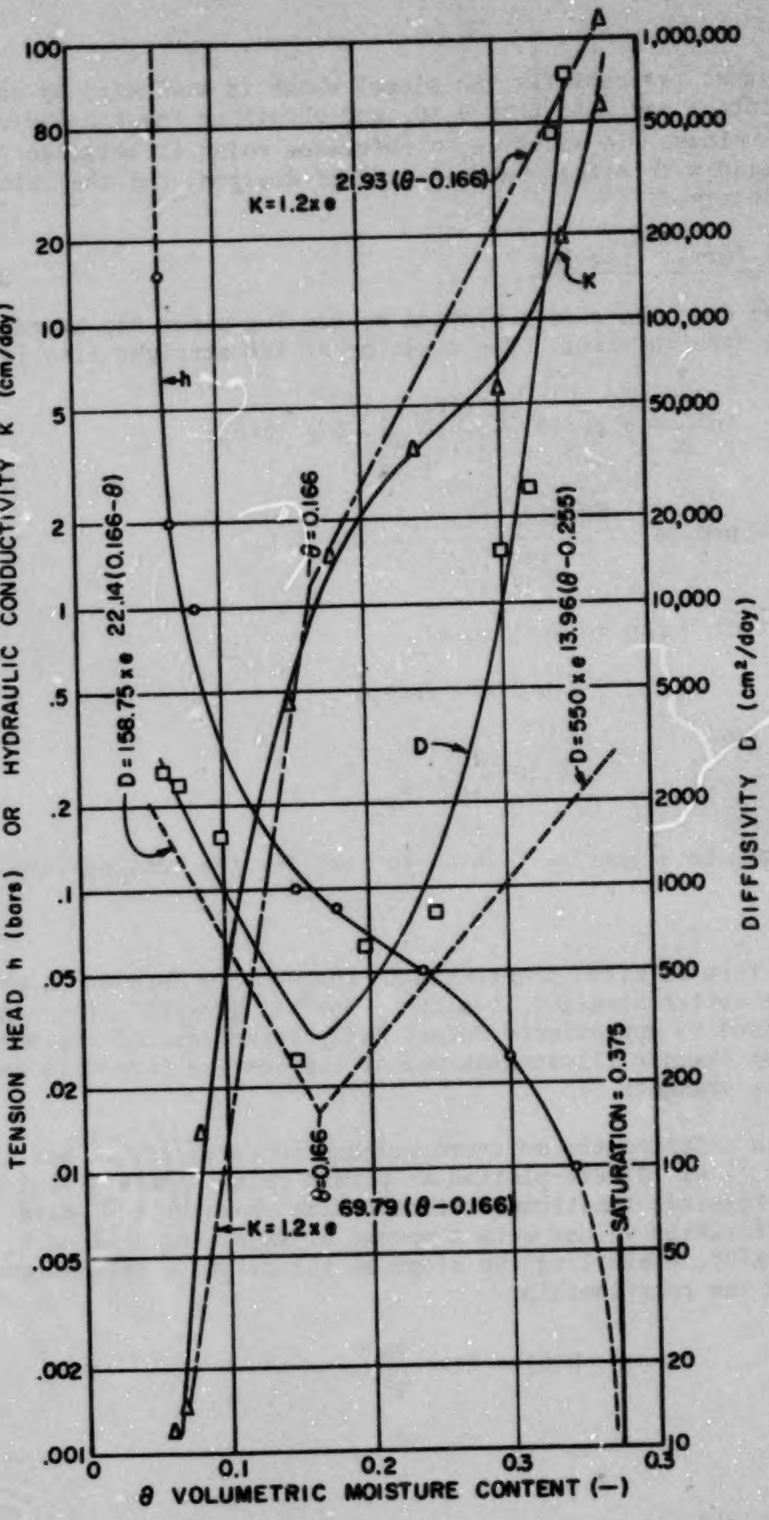


FIGURE 16. UNSATURATED FLOW PROPERTIES

Portions of the moisture-release curve exhibit very steep slopes making it difficult to evaluate $\partial h/\partial\theta$. At best, the procedure is approximate.

The dashed curves represent poor, though possible, approximations of the functions. They are used to illustrate the procedure. A single reference point is chosen for the conductivity functions:

$$\theta_r = 0.166 \quad \text{where } K_r = 1.2 \text{ cm/day}$$

Different reference points are chosen for each segment of the diffusivity relationship:

$$\theta_r = 0.166 \quad \text{where } D_r = 158.75 \text{ cm}^2\text{/day}$$

$$\theta_r = 0.255 \quad \text{where } D_r = 550 \text{ cm}^2\text{/day}$$

In general, reference points are chosen at the intersection of two straight line segments. This assures that values picked from the curve will produce the same value at the intersection by either relationship when the equations are used. Although this is good practice, it is not absolutely necessary.

In the Fortran coding for subrouting PRØP, it should be noted that the property relations can be extended below the TD value. In this case, the TD value passed in the call list is simply not used.

CAMPBELL'S METHOD FOR DETERMINING UNSATURATED FLOW PROPERTIES

Introduction

Gaylon S. Campbell(23) has proposed a simple method for developing the functional relationship between the moisture content and hydraulic conductivity. It is based on a relatively simple form of the moisture-release curve. Campbell found that agreement between conductivities calculated by this method with those experimentally determined for five soils was as good as with the Millington-Quirk method.

The soils tested included soils classified as loams, sandy loams, and sands. Saturated conductivities ranged from 0.0012 cm/min to 1.12 cm/min. Saturated volumetric moisture contents ranged from 0.35 to 0.52.

Because this method is simpler to use than the better known and widely accepted Millington-Quirk method, its use is appealing. In addition, it is easily extended to include the diffusivity function.

Theory

If a soil sample is saturated with water, the corresponding soil-water potential is atmospheric. As water is removed from the sample, the potential falls below atmospheric. Using atmospheric pressure as the gage reference, the soil water potential is negative. This is commonly denoted by referring to them as tensions.

A plot of the soil-water potential as a function of the volumetric moisture content is variously known as the moisture-release curve, moisture retention curve, or the moisture characteristic. If it can be represented by the functional relationship:

$$\psi_\theta = \psi_r \left(\frac{\theta}{\theta_r}\right)^{-b} \qquad [30]$$

the hydraulic conductivity is:

$$K_\theta = K_r \left(\frac{\theta}{\theta_r}\right)^{2b+3} \qquad [31]$$

where:	ψ is the soil-water potential	(L)
	ψ_θ denotes ψ at the arbitrary content θ	(L)
	ψ_r denotes ψ at the reference level θ_r	(L)
	θ is the volumetric moisture content	(L^3/L^3 or -)
	θ_r denotes θ at the reference level r	(L^3/L^3 or -)
	K_θ is the hydraulic conductivity at content θ	(L/T)
	K_r is the hydraulic conductivity at the reference content θ_r	(L/T)
	b is an empirical constant determined from the data	(-)

Equation [31] is based on the following assumptions:

a. Flow of water in the soil is controlled by the smallest of two pores in sequence.

b. Only pores that are connected together contribute to the total hydraulic conductivity (i.e., isolated and dead-end pores are not effective.

c. Pores fit together randomly.

Based on these assumptions, the pore radii and pore size distribution function are used to determine the conductivity. The pore radii are related to water contents by the moisture-release curve and the capillary-rise equation. A pore interaction term is used to modify the final conductivity function.

In addition to the conductivity, solution of the unsaturated flow equation requires the diffusivity. It is defined as the conductivity at a given moisture content divided by the corresponding slope of the moisture-release curve:

$$D_\theta = \frac{K_\theta}{\partial\theta/\partial\psi} \qquad [32]$$

where: D_θ is the diffusivity at content ∂ (L^2/T)

Based on equations [30] - [32], the diffusivity becomes:

$$D_\theta = \frac{b\psi_r k_r \theta^{b+2}}{\theta_r{}^{b+3}} \qquad [33]$$

The diffusivity at the reference level r can be found from equation [33] by setting $\theta = \theta_r$. Then:

$$D_r = \frac{b\psi_r K_r}{\theta_r} \qquad [34]$$

Dimensionless Forms

The preceding equations are easily recast into dimensionless form as follows:

$$\frac{\psi\theta}{\psi_r} = \left(\frac{\theta}{\theta_r}\right)^{-b} \qquad [35]$$

$$\frac{K\theta}{K_r} = \left(\frac{\theta}{\theta_r}\right)^{2b+3} \qquad [36]$$

$$\frac{D_r}{D_r} = \left(\frac{\theta}{\theta_r}\right)^{b+2} \qquad [37]$$

They are useful in comparing properties of different samples. Plots of each dimensionless property on log-log paper may be inspected for similarities and differences.

Evaluation of Empirical Constant b

It can be shown that a relationship of the form given by equation [30] will plot as a straight line on log-log paper. The slope is equal to the value of the empirical constant b. The following procedure can be used to determine b from a set of moisture retention data.

a. Plot ψ versus θ on log-log paper.

b. Fit a straight line through the data points.

c. Evaluate the fit. If it is unacceptable, Campbell's method cannot be used. An alternate method such as Millington-Quirk should be tried.

d. Select two points on the straight line. (Point 1 corresponds to the highest θ.)

e. Calculate b by either of the following equations:

$$b = -\frac{\log(\psi_2/\psi_1)}{\log(\theta_2/\theta_1)} \quad [38]$$

or

$$b = -\frac{\ln(\psi_2/\psi_1)}{\ln(\theta_2/\theta_1)} \quad [39]$$

Note that the base of the logarithm is irrelevant and b should be a positive quantity.

The θ's in the previous equations are volumetric. In general, laboratory data are reported on a gravimetric basis.

Thus:

volumetric - θ = volume of soil water/total volume of sample (L^3/L^3 or -)

gravimetric - α = weight of soil water/dry weight of soil (F/F or -)

It can be shown that:

$$\theta = \alpha\, BD/D_w \quad [40]$$

where: BD = bulk density of soil (i.e., dry weight of soil/unit volume of total sample) (F/L^3)

D_w = density of water (i.e., weight of water/unit volume of water) (F/L^3)

Substitution of equation [40] into equation [38] yields:

$$b = -\frac{\log(\psi_2/\psi_1)}{\log(\alpha_2/\alpha_1)} \qquad [41]$$

Consequently, determination of b can be based on either volumetric or gravimetric data. Similarly, any set of consistent units for the potentials may be used such as centimeters, inches, feet, or bars* since conversion from one set of units is merely ψ multiplied by a constant in which constants in numerator and denominator cancel.

Significance of Reference Level r

A specific state, termed the reference level, is noted and used in many of the previous equations. Certain variables are referenced to this level, as denoted by the subscript r. The reference level is merely the moisture level at which the hydraulic conductivity is known. Practically, the saturated conductivity K_s is most easily measured in the field or laboratory. Then

$$K_r = K_s \qquad [42]$$

$$\theta_r = \theta_s \qquad [43]$$

$$\psi_r = \psi_e \qquad [44]$$

Since D_r is computed from the above variables, it can be excluded. θ_s is the moisture content at saturation and ψ_e is the corresponding potential. ψ_e is called the air-entry potential. Its physical significance and determination are discussed in the next section.

Air-entry Potential, ψ_e

If a soil is saturated and at equilibrium with free water at the same elevation, the pressure is atmospheric and the tension head is zero.

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* 1 bar = 1 atmosphere 14.7 lb/in^2 which is equivalent to a column of water = 33.92 feet = 407.1 inches = 1,033 cm.

Hillel (24) states:

> "If a slight suction, i.e. a water pressure slightly subatmospheric, is applied to water in a saturated soil, no outflow may occur until, as suction is increased, a certain critical value is exceeded at which the largest pore of entry begins to empty. This critical suction is called the air-entry suction. Its value is small in coarse-textured and in well-aggregated soils. However, since in coarse-textured soils the pores are often more nearly uniform in size, these soils may exhibit critical air-entry phenomena more distinctly and sharply than do fine-textured soils."

Carefully run laboratory tests on undisturbed samples might provide a value for ψ_e. This has never been done by the Bureau of Reclamation. However, a suitable value might be obtained by extending the straight line of the log-log plot of potential versus moisture content to saturation.

A review of current literature reveals a lack of numeric values for the air-entry potential. However, values should range from 5 to 100 cm depending on the soil texture and pore size distribution. Lacking field data, the following values are suggested:

Texture	Range in ψ_e
sand	1- 5 cm
silt	10-20 cm
clay	40-60 cm

It is noted that ψ_e cannot assume a zero value since the relationship of equation [30] would be meaningless.

The air-entry potential concept is related to capillary forces. This suggests the use of the capillary rise equation for cylindrical tubes for soils on which a mechanical analysis is run. Based on a water temperature of 25° C (77° F), an assumed contact angle of zero, and the previously suggested air-entry values, the following equations are obtained:

$$r_{eff} = (10P_S + 3.3\ P_{SI} + P_C)/34{,}000 \qquad [45]$$

$$\psi_e = 0.147/r_{eff} \qquad [46]$$

where: r_{eff} = effective capillary radius of pores (cm)

P_S, P_{SI}, P_C = percent of sand, silt, and clay, respectively, based on the mechanical analysis

ψ_e = air-entry potential (cm)

An effective capillary tube radius is first computed using equation [45]. Since the larger pores drain first, this equation places the most weight on the sands and the least weight on the clays. The capillary rise equation [46] is then used to compute the air-entry value. If the soils are of uniform texture, the following values are given by the equations:

Texture (100%)	r_{eff} (cm)	ψ_e (cm)
sand	0.0294	5
silt	0.00971	15
clay	0.00294	50

There is no provision in equations [45] and [46] to include soil structure. At best, their use provides approximate air-entry values when measured data are lacking.

SECTION XI

USER'S MANUAL - DRAINOUT PROGRAM

INTRODUCTION

This program was designed to predict the response of a subsurface drainage system consisting of parallel, equally spaced tile drains to deep percolation inputs. Both the water table elevation midway between drains and the drain discharge are computed. In particular, this program was developed as part of a water quality simulation model with the computed monthly drain discharge acting as input to other programs.

The program may be used in two distinct ways:

a. Analysis. - An existing or designed drainage system can be analyzed for its response to a given set of deep percolation inputs.

b. Design. - Given the porous media properties, depth to barrier, effective drain radius, depth to drains, and the deep percolation schedule, the drain spacing that will adequately provide the specified drainage depth can be determined.

Techniques conform closely to those used routinely by the USBR in determining drain spacings. Details are given in the program description.

Deep percolation data can be inputed by either of two methods:

a. Magnetic tape input of daily values based on the results of an unsaturated flow model. This tape is written by an interface program.

b. Card input of values based on any desired method. They may be developed by considering crop type, agricultural practices, climatic conditions, and field experience.

Output includes listed results, an optional magnetic tape for use with a cathode ray tube plotting routine and optional punched output for use with the drain effluent prediction portion of the water quality model. (CRT plotting routines are not included in this report.)

UNIT NUMBERS

Five input-output devices are referenced by the program:

Unit designation	Unit description or purpose
1	The unit on which the magnetic tape containing deep percolation data is mounted. These data are written by the interface program and computed by the Unsaturated Flow Program.
3	The unit to which computed results are written on a saved magnetic tape. An entirely new tape may be written or results for additional years added to a previously generated tape. It is used in conjunction with the utility program to obtain plots of the results.
5	The common input tape or unit (CIT). It is the computer system's standard input device.
6	The common output tape or unit (CØT). It is the computer system's standard output device.
7	The punched card output device of the computer system.

DATA DECK STRUCTURE

There are six groups of input cards in the data deck, as shown in Figure 17.

Cards in groups 1 through 5 apply to both analysis and design. Most of the variables on these cards are identical for either use. However, certain variables are used in slightly different ways, others have unique restrictions, and some are not used for design. These are prefaced by an asterisk. Their use in design is discussed separately along with the group 6 card in the section, Design Inputs.

CARD GROUP 1 - Title Card

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	TITLE	An 80-character alphanumeric title used to identify all printed and plotted output. If this title is desired to be centered on output, it must be centered on the card.

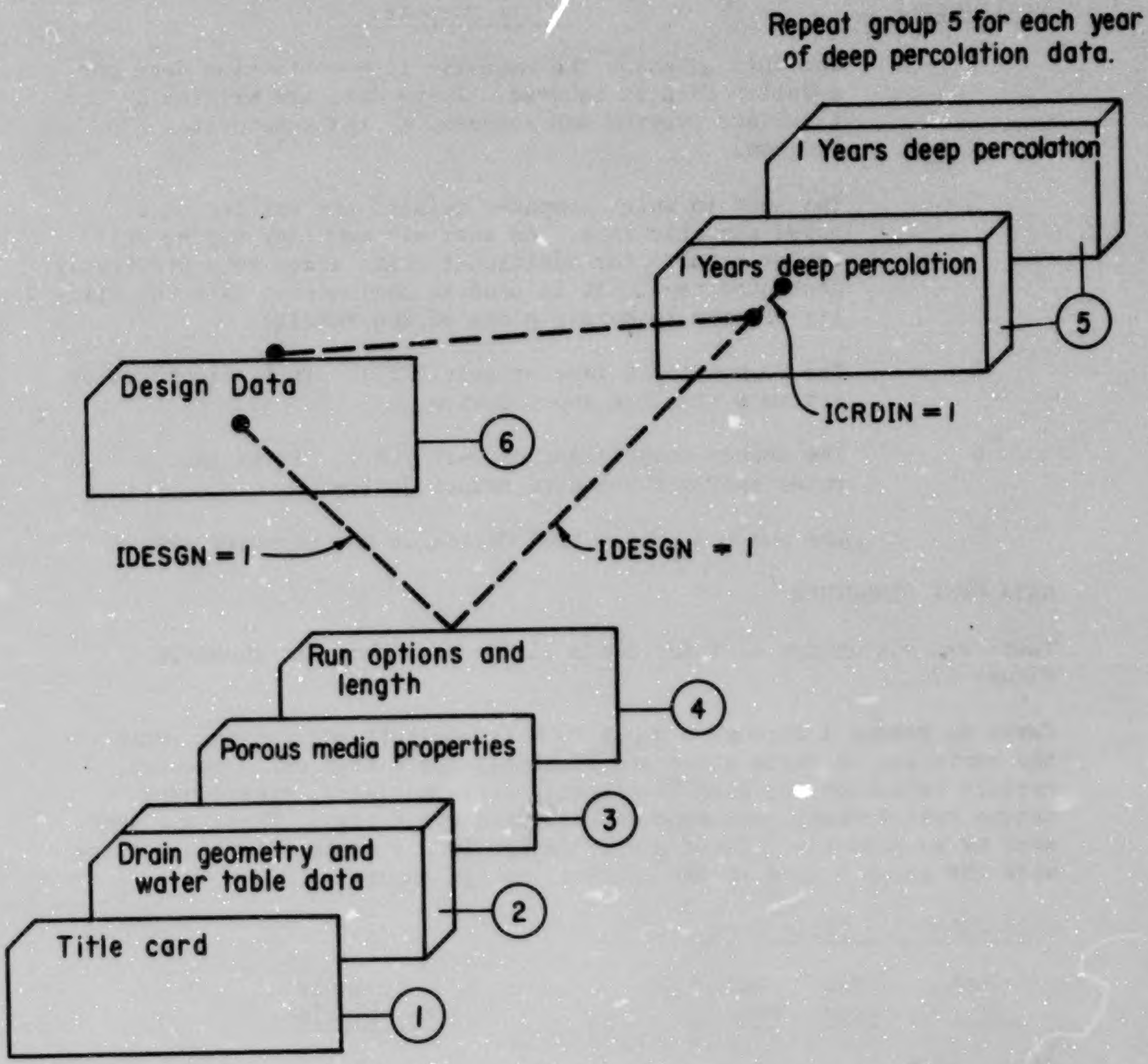

Repeat group 5 for each year of deep percolation data.
I Years deep percolation
I Years deep percolation
5
ICRDIN = I
Design Data
6
IDESGN = I
IDESGN = I
Run options and length
4
Porous media properties
3
Drain geometry and water table data
2
Title card
1

FIGURE 17. DATA DECK STRUCTURE-DRAINOUT SUBMODEL

Column No.	Var type	Var name	Variable description

CARD GROUP 2 - Drain Geometry and Water Table Data

For further clarification, see Figure 1. The water table position referred to by YSTRT, YEST, YLIM, and YTEST means the height of the water table above the horizontal centerline of the drains at a point midway between adjacent drains.

Card 1 of 2

Column No.	Var type	Var name	Variable description
1-10	R	SPACE	Drain spacing (feet).
11-20	R	D	Distance from horizontal centerline of drain to barrier (feet).
21-30	R	ER	Effective radius of drain (feet).
31-40	R	CLSTRT	Amount of deep percolation added to the aquifer on the first day (January 1) of the initial year of the run (acre-inches/acre or inches). (See RESTART OF PROBLEM.)
41-50	R	YSTRT	The water table position at the start of the initial year of the run (feet). This value can be negative, zero, or positive. (See NEGATIVE STARTING POSITION, RESTART OF PROBLEM.)
51-60	R	YEST	The estimated maximum water table position (feet). (See SELECTION OF DRAINAGE CASE.)
61-70	R	YLIM	The water table position below which the drainout is considered complete (feet). When the computed position is below this value, it is set to zero for output as is the discharge until another deep percolation occurs or the run ends.
71-80	R	YTEST	A test value used to determine when dynamic equilibrium is reached (feet). If the water table is within YTEST at the end of successive years, dynamic equilibrium is assumed. (See DYNAMIC EQUILIBRIUM.)

Card 2 of 2

Column No.	Var type	Var name	Variable description
1-10	R	DCSTRT	The value of the cumulative leachate or deep percolation at the start of the initial year when input is via magnetic tape 1 (cm^3/cm^2 or cm). (See DEEP PERCOLATION DATA.)
11-20	R	YBLIM	The absolute value of an instantaneous buildup (deep percolation/specific yield) which must be equaled or exceeded before it is applied (feet). (See APPLICATION OF METHOD.)
21-25	I	MXTDR	The maximum length allowed for a drainout period (days). (See APPLICATION OF METHOD.)

CARD GROUP 3 - Porous Media Properties

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	PERM	Aquifer permeability (feet/day).
11-20	R	SY	The storage coefficient expressed as a decimal (ft^3/ft^3 or dimensionless). It is often taken as the specific yield. It is the ratio of drainable or fillable voids volume to the total volume.

CARD GROUP 4 - Run Options and Length

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	I	NYRS	The number of years of deep percolation data to be processed for this run. Each year is one file on unit 1 when input is by magnetic tape or one set of group 5 cards when input is by cards. (See ICRDIN below.) It is noted that NYRS may be zero when the NOPT option is used to calculate the falling water table.

Column No.	Var type	Var name	Variable description
6-10	I	INFILE	The number of the initial file to be read on unit 1 when deep percolation inputs are by magnetic tape. (See RESTART OF PROBLEM.)
11-15	I	NØPT	Option to allow calculating drainout after the last year of deep percolation input data. If NØPT ≠ 1, the program stops at the end of the last year having inputs. If NØPT = 1, the program continues to compute results using zero inputs until drainout is completed according to YLIM.
16-20	I	NREPT	Option to allow repetition of the last year's deep percolation input data for successive years. The option is available for both card and tape input. Note that NØPT may be used in conjunction with NREPT. If NREPT ≤ 0, option is not used. If NREPT > 0, drainout calculations are continued with the last year of input repeated NREPT times, unless dynamic equilibrium is reached. (See DYNAMIC EQUILIBRIUM.)
21-25	I	NSAVE	Option to allow writing of daily and monthly results on unit 3. If NSAVE = 1, data are written. (See OUTPUT.)
26-30	I	NTYPE	Selects the drainage case to be used in the analysis. If NTYPE = 1, analyze as drains above barrier.

Column No.	Var type	Var name	Variable description
			If NTYPE = 2, analyze as drains on barrier. If NYTYPE = any other value, use the program criteria to select the case. (See SELECTION OF DRAINAGE CASE.)
31-35	I	IYEAR	The year number corresponding to the initial year being processed in the current run. It may be 1, 7, 1972, etc., and is used to identify output.
36-40	I	NPUN	Option to allow punching of the average monthly discharge for each year of the run. If NPUN = 1, then punch cards. (See OUTPUT.)
41-45	I	INFIL3	The number of the initial file to be written on unit 3. (See RESTART OF PROBLEM.)
46-50	I	ICRDIN	Option to allow input of deep percolation data by cards. If ICRDIN = 1, then input is by cards, group 5.
51-55	I	IDESGN	Option to specify the design mode. If IDESGN = 1, the program is to be used for design. If IDESGN ≠ 1, the program is to be used for analysis.

CARD GROUP 5 - Deep Percolation Data (ICRDIN = 1 Only)

Card 1 of ?

Column No.	Var type	Var name	Variable description
11-12	I	IMØN	Number corresponding to month of application (i.e., January is 1, June is 6, etc.).

Column No.	Var type	Var name	Variable description
13-14	I	IDAT	The date of the month of application (i.e., an application on February 12 is IMØN = 2, IDAT = 12).
15	A	ADENT	A single alphanumeric character which can be used to designate the type or source of deep percolation (i.e., I for irrigation, P or R for precipitation, etc.). It is printed on output.
16-20	R	AMT	Amount of deep percolation on the given date (acre-inches/acre or inches).

Note: The IMØN, IDAT, ADENT, AMT is repeated for each application with seven values per card. The applications need not be in chronological order, except they must be in groups by years, with the first application being first and the last application being last for each year. The end of a year's input is indicated by a blank IMØN, IDAT, ADENT, AMT set. If the number of applications in a year is a multiple of 7, then an additional blank group 5 card is required. (See DEEP PERCOLATION DATA.) A perpetual calendar is used so that no application should be made on February 29.

The deep percolation inputs for a given day are assumed to occur throughout the day. They are applied as an instantaneous deep percolation at 12 midnight (i.e., at the start of the next day). Consequently, an initial application on the first day of the initial year must be specified by the value of CLSTRT (card group 2).

DESIGN INPUTS

The section entitled Design Method should be consulted for clarification of the design inputs.

CARD GROUP 2

Card 1 of 2

1-10	R	SPACE	Initial trial drain spacing (feet). If the Donnan formula is used, SPACE should be left blank.

Column No.	Var type	Var name	Variable description
51-60	R	YEST	The design maximum water table position (feet).

CARD GROUP 4

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-5	I	NYRS	The number of years of deep percolation data to be processed for this run. For design, only a single year of inputs is allowed. Therefore, NYRS must equal 1. (See INPUT CHECKS AND ERROR MESSAGES.)
11-15	I	NOPT	This option has no significance when the design mode is being used and is ignored.
16-20	I	NREPT	The maximum number of years allowed to reach dynamic equilibrium for one trial spacing. (See INPUT CHECKS AND ERROR MESSAGES.)
21-25	I	NSAVE	For design, only the results for the correct drain spacing (i.e., the designed spacing) at dynamic equilibrium are available for output. If the spacing is not determined, there are no water table or drain discharge results. Therefore: NSAVE. - The daily and monthly results at dynamic equilibrium for the designed system are written on unit 3 when NSAVE = 1. IYEAR. - The year number associated with the results at dynamic equilibrium. NPUN. - The average monthly discharge values for the designed system at dynamic equilibrium are punched when NPUN = 1.
31-35	I	IYEAR	
36-40	I	NPUN	

Column No.	Var type	Var name	Variable description
41-45	I	INFIL3	The number of the initial file to be written on unit 3. It is noted that multiple files may be written on unit 3, even though each file represents a different drainage system.

CARD GROUP 6 - Design Data (IDESGN = 1 only)

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	I	IMØNST	Number of month corresponding to start of period from which SEEP is computed (i.e., January is 1, June is 6, etc.).
6-10	I	IDATST	The date corresponding to the start of period given by IMØNST.
11-15	I	IMØNFI	Number of month corresponding to end of period from which SEEP is computed.
16-20	I	IDATFI	The date corresponding to the end of period given by IMØNFI.
21-25	I	NTRYMX	Maximum number of trial spacings allowed.
26-35	R	YCHECK	The absolute value of the difference between the computed maximum rise at dynamic equilibrium and the design value YEST which cannot be exceeded when the drains are properly spaced.
36-45	R	SEEP	Steady-state seepage rate to be used when the Donnan formula is used for the initial spacing (feet/day).

SELECTION OF DRAINAGE CASE

The USBR drainage design procedures make use of the two limiting cases:

a. Drains an infinitely long way above an impervious barrier.

b. Drains resting on an impervious barrier.

Any real system must fall between these extremes. Based on experience, the USBR has found the following criteria useful in selecting the appropriate case:

a. $D/YEST \leq 0.1$, analyze as drains on a barrier.

b. $D/YEST \geq 0.8$, analyze as drains above a barrier.

c. $0.1 < D/YEST < 0.8$, analyze both ways and use the results with discretion. (The program analyzes this case as drains above a barrier.)

Here, D is the distance from the horizontal centerline of the drain to the barrier, and YEST is the maximum water table rise above the drains at the midpoint between drains.

Although the criterion of (c) is not particularly satisfying, it is a practical recommendation since the drainage system may mathematically approach both limiting cases at different times. Improved accuracy dictates use of the nonlinear solutions of Moody.(11)

The value of YEST is an input. Since the true value is unknown until the analysis is completed, the input value is only an estimate (or the design value when in the design mode). If an estimate is not made and YEST is less than or equal to 0.01 foot (essentially zero), the ratio D/YEST is presumed unknown. The value of D is then used to select the case - if D is equal to or greater than 1.0 foot, analysis is for drains above a barrier.

The program criteria can be overridden by means of the input variable NTYPE. A value of 1 selects the case of drains above a barrier while a value of 2 selects the case of drains on a barrier. Use of this variable permits analysis by both cases in the intermediate range, though this must be done by separate runs.

The flow chart of Figure 18 summarizes the selection process.

Note that it is possible to specify an analysis by the wrong method according to either criteria (a) or (b). This situation is noted on output, as is a recommendation that the intermediate range be analyzed as both cases. The method of analysis, how it was selected, and the recommended method of analysis based on the computed results are printed on output, both for design and analysis.

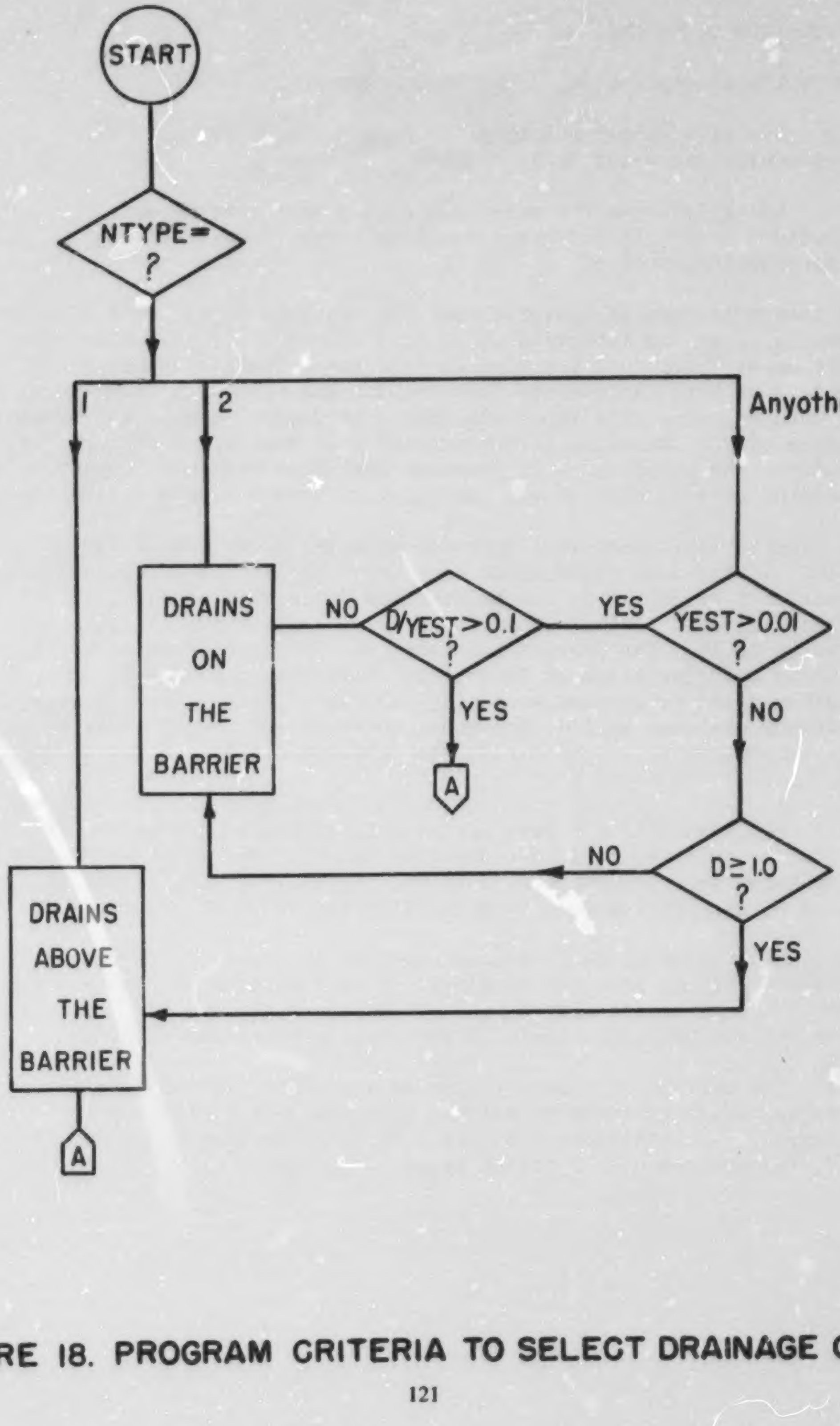

START
NTYPE=
?
1
2
Anyother
DRAINS
ON
THE
BARRIER
NO
D/YEST>0.1
?
YES
YEST>0.01
?
YES
A
NO
NO
D≥1.0
?
YES
DRAINS
ABOVE
THE
BARRIER
A

FIGURE 18. PROGRAM CRITERIA TO SELECT DRAINAGE CASE

APPLICATION OF METHOD

Two problems arise in using the USBR drainage methods:( )

a. Use of a linear solution for long drainout periods overestimates the water table decline.

b. Reinitializing the water table when an instantaneous buildup occurs introduces volumetric errors because of the mathematics involved.

The latter problem is insignificant for semiarid areas where deep percolation occurs at intervals of 10 days or more. It is serious for humid areas where deep percolation from precipitation occurs frequently, or when unsaturated flow results are used on a daily basis (as when magnetic tape input via unit 1 is used). Errors in the mass balance of the saturated system are the best indicators of this difficulty. The solution is to increase the short drainout periods by combining several days of deep percolation into a single application.

The program implements this approach by means of the input variable, YBLIM. If the deep percolation on a given day is not sufficient to attain this value, it is accumulated and drainout proceeds. The next buildup is added to this accumulated value and the sum is again compared to YBLIM. The process continues and is repeated as necessary. By using a larger value of YBLIM, the short drainout periods are lengthened and mass balance usually improves. Rather than specifying a minimum drainout period, the above approach was used because it is more responsive to variations in the deep percolation inputs during a run.

Since deep percolation inputs may produce either an instantaneous buildup or decline, it is the absolute value of the accumulated deep percolation that is compared to YBLIM. If YBLIM is left blank or set to 0, the program uses an internally set value of 0.1 foot.

The first problem of long drainout periods is corrected by subdividing these periods into two portions. A zero buildup is assumed, the water table is reinitialized, and the drainout process begins again. There are two means available in the program to accomplish this:

a. The maximum allowable length of a drainout period in days can be specified on input by MXTDR. If a drainout period reaches this length, reinitialization occurs. If MXTDR is left blank or set to 0, the program uses a preset value of 60 days.

b. A fictitious, near zero, deep percolation can be added on the day when reinitialization is desired. This approach is useful when input is by cards, but cannot be used with tape input. The magnitude of the application must be sufficient to exceed the value of YBLIM which, as noted above, cannot be set to zero exactly. In general, if SY is the specific yield, the required value is YBLIM x SY x 12 inches. When the value of YBLIM is not important (the usual case when input is by cards), the values of YBLIM and MXTDR can be chosen to insure the desired result. For example, if YBLIM = 0.0001 foot and SY = 0.1, a fictitious application of (0.0001)(.1)(12) = 0.00012 inches is used on the desired dates. The value of MXTDR is then set to a large value (say 365) to assure it does not shorten the desired drainout period.

DYNAMIC EQUILIBRIUM

If the same annual set of deep percolation inputs is used for successive years, the drainage cycle will approach a repeating annual pattern. When this repeating cycle is attained, "dynamic equilibrium" is said to have been achieved. It is this condition for which the USBR designs drains.

A convenient test for dynamic equilibrium is based on the comparison of the water table position for successive years at the same time within the annual cycle. Year-end values are practical for this purpose, and the variable YTEST is read for the test. Its value can be picked to obtain as strict a tolerance as desired. The smaller the value, the more cycles required to satisfy the test.

In the program, testing for dynamic equilibrium does not occur until all years of deep percolation inputs have been read (NYRS) and the repetition mode is being used (NREPT > 0). Computations terminate when the year-end water table positions are within YTEST.

DEEP PERCOLATION DATA

There is no restriction on the sign of the deep percolation inputs. A positive value denotes water being added to the saturated system while a negative one denotes water being removed. The latter case results when unsaturated flow phenomena are explicitly used and evapotranspiration produces upward flow.

The program allows deep percolation inputs on a daily basis. Deep percolation occurring on a given day is assumed to be applied at the end of the day (at the start of the next day). For example, an application on June 6 is applied as an instantaneous buildup or decline at the start of June 7.

Computations are performed day by day for an entire year. Partial years are not allowed. Deep percolations read from cards include the date on which they occur. All other days are assumed to have zero inputs.

Tape input using unit 1 is on a daily basis, starting with some initial day and ending with some final day. Days preceding the initial or following the final are assumed to have zero inputs. Organization of the tape is shown in Figure 19. Because this tape is also used for plotting unsaturated flow results, it contains information not needed by the drainout program. In particular, only the Julian day and the cumulative leachate are used.

The cumulative leachate refers to the accumulated amount of water that was leached from the unsaturated into the saturated system. The drainout program uses the cumulative amounts on successive days to compute the deep percolation by taking the difference. Since the drainout program can be restarted and may be run using data starting with a year other than the first, the initial cumulative leachate for computing the first day's input is required. This is inputed by the value of DCSTRT. Once the program is running, the cumulative values are carried automatically.

The correct starting year is selected by means of the input variable INFILE, described in the next section.

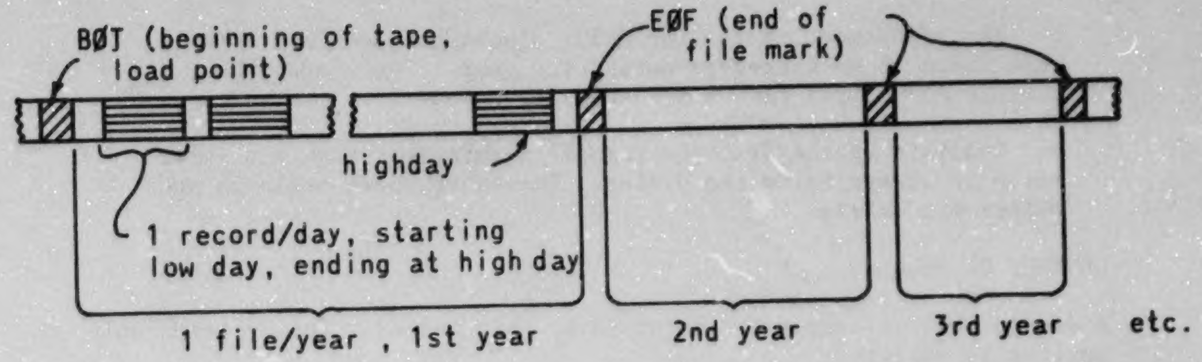
NEGATIVE STARTING POSITION

The water table position at the start of the initial year of the run, YSTRT, may be specified as negative. A horizontal water table is assumed as long as it is at or below the drain level.

Logically, use of a negative starting position is limited to the analysis mode. The gradual buildup of the water table to the drain level can then be followed. For design, a negative YSTRT merely wastes computer time since the dynamic equilibrium condition is required for design.

The following minor modifications to the computations and output are noted:

a. Although mass balance results are printed, the water in storage above the drains will be negative. It does not represent a true quantity of water since the drain acts as the reference level. However, the change in storage during the year is correct.


BØT (beginning of tape, load point)
EØF (end of file mark)
highday
1 record/day, starting low day, ending at high day
1 file/year , 1st year
2nd year
3rd year
etc.

Each daily record is written by the binary write statement:

```
  WRITE (2) I YEAR, II, XT, CL, DEFAMC, CI, HED, ETS, N, (TN(J),
  Z(J), SF(J), U(J), J=1,N)
```

where

1 YEAR	is the year number
II	is the Julian day
XT	is the decimal part of the day (will always be 1.0 for end of day)
CL	is the cumulative leachate from unsaturated zone (cm)
DEFAMC	is the cumulative evapotranspiration that could not be supplied to the crop because of low moisture contents (cm)
CI	is the cumulative infiltration at the surface (cm)
HED	is the amount of water at the surface, remaining to infiltrate (cm)
ETS	is the net amount of water which has passed through the surface in either direction(cm)
N	is the number of nodes in the column
J	is the particular node number
TN(J)	is the volumetric mositure content (dimensionless)
Z(J)	is the evapotranspiration not supplied since the last output time on tape 5 (see unsaturated flow program) (cm)
SF(J)	is the amount of water that has moved between node J and J 1 since the last output time on tape 5 (cm)
U(J)	is the evapotranspiration rate (cm/day)

FIGURE 19. ORGANIZATION-DAILY MOISTURE TAPE

b. The adjustment factor for daily discharges does not apply when there is no discharge during the year. Therefore, the message ADJUSTMENT FACTOR NOT REQUIRED appears.

c. Analysis of the drainage case is meaningless when the water table is always below the drains. Therefore, both analysis and output are deleted.

RESTART OF PROBLEM

A design problem cannot be restarted by this method. This section only applies to analysis.

CLSTRT has been defined as the amount of deep percolation to be added on the first day of the initial year of the run. As noted in the previous section, deep percolation occurring on a given day is applied at the start of the next. Therefore, an input on December 31 of the previous year is carried over and applied on January 1. To allow for this carryover on the initial year of the run, its value must be read. The carryover for subsequent years is automatic. On completion of a run, the value of CLSTRT for the next year is printed. It includes the actual deep percolation of December 31 plus any accumulated deep percolation not yet applied due to use of YBLIM. (See APPLICATION OF METHOD, p. 122.)

The water table position at the end of the run is also printed. It should be used as the value of YSTRT if the problem is restarted for the next year.

When a problem is restarted, it is necessary to position the input and output tapes on units 1 and 3 for the first operation if they are used. This is accomplished by means of the inputs INFILE and INFIL3. INFILE is the initial file to be read on unit 1 while INFIL3 designates the first file to be written on unit 3. Since each file corresponds to a single year's data, the word file is synonymous with year.

The program skips over (INFILE-1) or (INFIL3-1) files and positions the tape at the start (first record) of the initial file. For the first run of a problem, the file numbers may be set to 1 or left blank. For subsequent runs, they must be set correctly. As an example:

a. Input tape 1 contains 3 years of data, with the third year representing an average annual input to be used for subsequent years.

b. The initial run computed results for 5 years.

c. To restart the problem at the 6th year, INFILE = 3 and INFIL3 = 6.

DESIGN METHOD

The determination of the proper drain spacing is a trial-and-error process. An initial spacing is selected and the response of the drainage system to the deep percolation inputs is analyzed. The maximum water table rise at dynamic equilibrium is then compared with the design value. If the computed rise is greater, the drains must be spaced closer while a smaller computed rise means the drains may be spaced farther apart.

Special considerations for design include:

a. Selection of the initial spacing.

b. Criteria for deciding when an adequate design has been found.

c. Method of adjusting the trial spacings to arrive at the design spacing.

Each of these items is now discussed.

Design Method - Selection of Initial Spacing

There are two alternatives available to the program user:

a. The initial spacing can be specified on card 1 of group 2 as SPACE. This may be based on experience, a rational analysis, or pure guess.

b. The steady state Donnan formula can be used. This formula makes use of a steady deep percolation rate (seepage across the water table).

In practice, the steady-state seepage rate, SEEP, is usually based on the deep percolation from one irrigation averaged over the time between irrigations during the peak of the irrigation season. As such, it represents a maximum rate at which water must be drained in order to provide a sufficient drainage zone. Experience has shown that when drains are on the barrier, this rate may be halved.

The steady seepage rate can be specified by the input variable SEEP on the group 6 card. Alternately, the user may specify the starting (IM0NST, IDATST) and ending (IM0NFI, IDATFI) inclusive dates for a period over which the average seepage rate is computed. The total deep percolation for the period is used with the length of the period to compute SEEP. If the starting date is not specified, it is taken as January 1 while December 31 is used when the ending date is not specified.

In summary:

a. If SPACE > 0, it is used as the initial spacing even though a value of SEEP or the period dates are specified.

b. If SPACE $\leq$ 0, the Donnan formula is used.

When the Donnan formula is used:

a. If SEEP $\geq$ 0, it is used.

b. If SEEP is $\leq$ 0, the seepage rate is based on deep percolations during the period IM0NST, IDATST through IM0NFI, IDATFI. If the dates are not specified, the period is taken as January 1 through December 31.

Design Method - Criteria of Adequate Design

The design maximum rise is given as YEST on card 1 of group 2. If the computed maximum rise at dynamic equilibrium is YMAX, the design is deemed adequate when the absolute value of (YMAX - YEST) is less than or equal to YCHECK. Here YCHECK is the tolerance read from the group 6 card.

If YCHECK $\leq$ 0, the program uses a default tolerance of 0.5 percent of YEST. Thus, if YEST = 4.0 feet, YCHECK = 0.02 feet. Should YCHECK < YTEST (the value used to determine when dynamic equilibrium is reached), it is probable that an adequate design will not be found. This is particularly true if YCHECK is much smaller than YTEST. To avoid this possibility, the program resets YCHECK to YTEST if YCHECK < YTEST.

The maximum number of trial spacings is specified as NTRYMX on the group 6 card. If a satisfactory design is not obtained after NTRYMX trials, a message is printed and execution terminates. When NTRYMX is not specified, a program default value of 20 is used. This is also the maximum value. Should the user specify NTRYMX > 20, the program resets it to 20.

Design Method - Spacing Algorithm

When the first trial design is finished, the program uses the YCHECK criteria to determine whether an adequate design has been found. If it has not, the spacing is either doubled or halved depending on the results. If the spacing is doubled, it must also meet the requirement that the new spacing be at least 100 feet. This procedure is continued until spacings both greater and smaller than the correct design are found. With the correct spacing bracketed, the computed maximum rises are used in conjunction with the design value and linear interpolation to obtain future trial spacings.

Normally, three trials result in the correct spacing. Thus, the initial spacing is not critical.

INPUT CHECKS AND ERROR MESSAGES

A number of logical checks are made on the input data. Failure to meet any of the tests results in an error message. These messages are listed and explained in the next subsection. They are prefaced by the notation:

```
******** ERRORS IN INPUT DATA ********
```

In addition, either of the following messages may appear when the design mode is used:

```
* MAXIMUM NO. TRIALS REACHED, SPACING NOT FOUND

* DYNAMIC EQUILIBRIUM NOT REACHED, TERMINATE **
```

The first message results when the limit NTRYMX is reached without the spacing being determined according to the YCHECK criteria. The second message is obtained when dynamic equilibrium is not reached using the YTEST criteria by NREPT years.

Should any of these errors be detected, the termination message:

```
******** EXECUTION TERMINATED ********
```

is written. When a normal termination is obtained after all computations are finished, the message:

```
******** COMPUTATIONS FINISHED. NORMAL EXIT. ********
```

is written.

OUTPUT

Program output consists of printed listings, punched cards, and computed results written on magnetic tape.

Printed data listed by the program on unit 6 is standard output. It includes:

a. Input data read from cards including deep percolation inputs when ICRDIN = 1.

b. A mass balance summary for each year of the run.

c. The volume of water removed by the drains for each day along with monthly and annual values as well as the percent each month is of the annual total.

d. The water table position for each day, as well as the minimum and maximum rises and their dates.

e. The restart parameters YSTRT and CLSTRT for future years.

f. The method of analysis (case) used as well as the recommended case.

Punched card output is written on unit 7 by the program. This output is optional, being selected by NPUN = 1. It consists of a title card identical to the group 1 card on input followed by pairs of cards containing monthly drain discharge volumes for each year of the run (or dynamic equilibrium year for design). The volume cards have the form

```
IYEAR, ICRD, (QMØN(I), I = 1, 6)
```

punched using an I5,I2,6E12.5 format. Here

a. IYEAR is the year number.

b. ICRD is the card order within the year. ICRD = 1 contains data for the first 6 months and ICRD = 2 contains data for the second 6 months.

c. QMØN(I) are the individual monthly volumes.

This card output is intended for use as input to the drain effluent prediction program (DE0200) of the irrigation return flow quality model.

Computed results are written by the program on unit 3 as optional output when NSAVE = 1. Each year's output is one file on unit 3.

Four logical records are written in each file as shown in Figure 20. These include:

a. Title information, the date of the computer run, and the year number of the computed results.

b. Daily water table position.

c. Daily discharge volumes.

d. Monthly discharge volumes and the annual value.

All data is written without format in binary form. The magnetic tape is intended as input to the utility program UT06 which plots computed drainout results on a cathode ray tube.

Logical Error Messages

The following is a complete list of error messages:

```
EM1 - DRAIN SPACING = ?  LE 0.0
EM2 - DESIGN MAX RISE = ?  LE 0.0
EM3 - NO. YEARS OF DEEP PERC. INPUTS = ?  MUST BE 1 FOR DESIGN
EM4 - DEPTH TO BARRIER = ? NEGATIVE
EM5 - EFFECTIVE RADIUS = ?  LE 0.0
EM6 - PERMEABILITY = ?  LE 0.0
EM7 - STORAGE COEFFICIENT = ?  LE 0.0 OR GE 1.0
```

EM1 applies only to analysis, EM2 and 3 only to design, while the remainder apply to both design and analysis. Each is discussed below:

EM1 - The drain spacing SPACE must be specified as a nonzero positive quantity for analysis.

EM2 - Drains cannot be designed unless the design rise YEST is specified as a nonzero positive quantity.

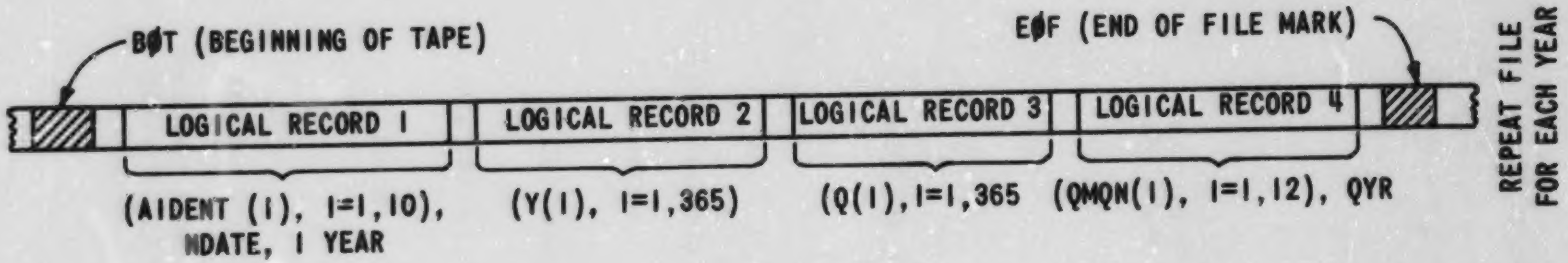
EM3 - Only a single design year of deep percolation inputs, NYRS, is permitted.

EM4 - The drains must rest on or be above the barrier material; hence, D must be zero or positive.

EM5 - The drains must have a finite effective radius, ER.

EM6 - The permeability, PERM, must be a nonzero positive quantity.

EM7 - The storage coefficient, SY, must exceed zero if a transient solution is possible and must not equal unity by definition.


BØT (BEGINNING OF TAPE)
EØF (END OF FILE MARK)
LOGICAL RECORD 1
LOGICAL RECORD 2
LOGICAL RECORD 3
LOGICAL RECORD 4
REPEAT FILE FOR EACH YEAR
(AIDENT (I), I=1,10), NDATE, I YEAR
(Y(I), I=1,365)
(Q(I),I=1,365
(QMQN(I), I=1,12), QYR

NOTATION

AIDENT(I) - 80 character alphanumeric title
NDATE - date of the computer run
IYEAR - year number of computed results
Y(I) - water table position for Julian day I
Q(I) - daily drain discharge for Julian day I
QMQN(I) - monthly drain discharge for month I
QYR - annual drain discharge for year I year

FIGURE 20. ORGANIZATION OF MAGNETIC TAPE OUTPUT
DRAINOUT SUBMODEL

SECTION XII
USER'S MANUAL
INTERFACE FOR CHEMISTRY PROGRAM

INTRODUCTION

This program converts data generated by the Unsaturated Flow Submodel to forms suitable for input to the Unsaturated Chemistry and Drainout Submodels.

The conversion for Unsaturated Chemistry involves a transfer from a nodal concept in Unsaturated Flow to a segment concept in Unsaturated Chemistry. Soil water flux and content values at each node are transformed to (1) mean or representative flux values at the upper and lower boundaries of each soil segment and (2) mean or representative soil water contents for each segment (segment volumes). This procedure is repeated for each time step being used in Unsaturated Chemistry. A commonly used time increment in 0.1 day.

At the end of each day, Interface can write binary information to unit Tape 2. This information for Drainout is similar to the data read from input unit Tape 3 with the exceptions that Q has been added, and DEFAMC and K have been deleted. Additional information can be found in the DATA DECK STRUCTURE and TAPE OUTPUT DETAILS sections.

The current version of the Interface Program is designed to convert data from 21 moisture nodes to data suitable for 10 soil segments plus one segment to account for water applications at the surface. A more generalized program could be developed at a future date. However, it is possible to modify the program for other nodal and segment combinations provided a few relationships are considered.

In general, a workable procedure is to determine the number of soil segments needed based on dispersive considerations and then compute the number of nodes to be used in Unsaturated Flow from the equation:

$$\text{No. Nodes} = \text{No. segments} * N + 1 \qquad [47]$$

Where:

$N = 1$, or 2 or 3 . . .

No. segments = the number of soil segments not counting the segment for surface applications

It is not recommended to use a value for N less than 1. Increasing the magnitude of N increases the number of nodes, thus increasing the accuracy and computer execution time of the Unsaturated Flow Submodel. Using 10 soil segments, values for N of 2 or 3 have proven to be adequate.

The number of terms in the equation for segment volume given in the Interface Program listing (card label, INTG 250) is given by

$$\text{No. Terms} = N + 1 \qquad [48]$$

The first and last terms carry half the weight of the remaining ones. The sum of the weighting fractions must equal the segment length in cm. Segment length is computed by

$$\text{Seg. Length (cm)} = \frac{\text{Length of Soil Column (cm)}}{\text{No. segments}} \qquad [49]$$

The "DO Loop" parameters (Card label, INTG 230) must be set as follows:

First Parameter - equals 1
Second Parameter - equals N*(No. segments - 1) +1
Third Parameter - equals N

The "DO Loop" parameters (card label, INTG 280) must be set as follows:

First Parameter - equals N +1
Second Parameter - equals N*(No. segments - 1) +1
Third Parameter - equals N

Implied "DO Loop" termination in write (1) statement must be changed to correspond to number of soil segments +1.

The card labeled INTG 350 must be set as follows:

MOISIN(M) = SF(M1)

where: M equals the number of segments +2.
M1 equals the number of nodes -1.

UNIT NUMBERS

Five file units are used by the Interface Program. Tape 3 is understood to contain the binary output data written by the Unsaturated Flow Submodel. Unsaturated Flow writes this data set out to Tape 5, and Interface accepts it as input on Tape 3.

Interface writes binary output to Tape 1 which is read by Unsaturated Chemistry on unit Tape 1. Binary output data may be written to Tape 2 in a form suitable for input to the Drainout Submodel via its Tape 1.

In addition, use is made of the common input and output file units.

DATA DECK STRUCTURE

Data from two basic card groups are read from the common input file. These groups contain title and control information.

CARD GROUP 1 - Title Information

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	AID	Title or heading information used to identify problem. Title is printed on output.

CARD GROUP 2 - Control Information

Column No.	Var type	Var name	Variable description
1-5	I	Q	The number of moisture nodes used in Unsaturated Flow Submodel.
6-10	I	IPRINT	Print interval for output listing of data being written to Tape 1. Value does not affect write interval to Tape 1.
11-15	I	INFILE (1)	Initial file to use on Tape 1
16-20	I	INFILE (2)	Initital file to use on Tape 2
21-25	I	INFILE (3)	Initial file on unit Tape 3
26-30	I	IRECB (1)	First record initial file on unit Tape 1
31-35	I	IRECB (2)	First record on initial file on unit Tape 2
36-40	I	IRECB (3)	First record on initial file on unit Tape 3.
41-45	I	LSFILE	Last file for unit Tape 3

Column No.	Var type	Var name	Variable description
46-50	I	IRECB	Last record for unit Tape 3
51-55	I	NOREC	No. of records in full file on unit Tape 3.
56-60	I	NSAVE2	If = 1, Tape 2 is written in form suitable for input to Drainout Submodel. If = 1, Tape 2 is not written.

TAPE OUTPUT DETAILS

Tape 1 - Output to Unsaturated Chemistry Submodel
WRITE (1) (IYEAR), II, INT, JDUM, SEGVOL (J) MOISIN (J), MOISONT (J), TEN, U(J), J=1, 11)

Variable name	Variable description
IYEAR	The year number.
II	The Julian day number.
INT	The time step within each day.
JDUM	A dummy variable reserved for future use.
SEGVOL (J)	The volume of water (cm^3/cm^2) contained in each soil segment, J. Note: Segment SEGVOL (1) contains water ponded on soil surface.
MOISIN(J)	The flux of water (cm^3/cm^2) across the upper boundary of segment J.
MOISOUT(J)	The flux of water (cm^3/cm^2) across the lower boundary of segment J.
TEN	A dummy value for soil water tension set equal to 300 cm water. Values for TEN must be computed for each segment in some applications of Unsaturated Chemistry.

Variable name	Variable description
U(J)	The consumptive use of water (cm^3/cm^2/day) for segment J. <u>Note</u>: If uptake of NH_4^+ and NO_3^- is taken to be proportional to consumptive use, then U(J) must be expressed in terms of cm^3/segment/time step.

Tape 2 - Output to Drainout Submodel

```
WRITE (2) IYEAR, II, XT, CL, CI, HED, ETS, Q, (TN(J), Z(J), SF(J),
  U(J), J=1,Q)
```

IYEAR	The year number.
II	The Julian day number.
XT	The fraction of a day when the data were written (e.g., 0.1 day, 0.2 day, etc.)
CL	Cumulative deep percolation (cm^3/cm^2)
CI	Net infiltration from applied water and errors in handling the upper boundary (cm^3/cm^2).
HED	Water standing at surface (cm).
ETS	Total quantity of water crossing surface boundary (cm^3/cm^2)
Q	Number of moisture nodes.
TN(J)	Volumetric moisture content (cm^3/cm^2) at time XT for Node J.
Z(J)	Deficit moisture (cm^3/cm^2) at Node J during the last time interval written to Tape 5 by Unsaturated Flow.

Variable name	Variable description
SF(J)	Total soil water flux (cm^3/cm^2) between Node J and (J+1) during the last time step written to Tape 5 by Unsaturated Flow.
U(J)	Evapotranspiration rate at Node J (cm^3/cm^2/day).

SECTION XIII

USER'S MANUAL

UNSATURATED CHEMISTRY PROGRAM

INTRODUCTION

The purpose of this manual is to provide the user with detailed operating instructions for the Unsaturated Chemistry Program. The manual is written with the assumption that the user has read the sections of this report and related references pertaining to the program's concepts and theoretical basis. The manual includes specific discussions of the types of data needed to run the program. Use or generation of all input and output media such as printed output, data cards, magnetic tapes, and disks is discussed in detail.

The source program is written in FORTRAN IV computer language for a Control Data Corporation CYBER 74-28 machine. The program as compiled under the Fortran Extended Compiler requires 105K octal to load and 75K to execute.

CARD GROUPS

The basic card groups needed to run the program are illustrated in Figure 21. Those groups marked with a dot must be omitted from the deck when the nitrogen portion of the model is bypassed (NBYPAS = 1). Group 6.5 must be included in the deck when the salt portion of the model is bypassed (SBYPAS = 1). At all other times, group 6.5 is omitted.

In a similar manner, group 7 is included in the deck only when flow data are to be read from cards (ITEST = 1). When ITEST = 0, flow data are read from tape 1.

Group 8 contains the initial soil analysis and must be present when the program is started from time zero (IRERUN = 0). When IRERUN = 1, group 8 is deleted from the deck.

Group 9, the restart data, is punched by the program at the conclusion of a run provided IPUNCH = 1. Group 9 is read into the program and must be present when IRERUN = 1 and IREADP = 1. If IRERUN = 1, but IREADP = 0, group 9 is not included, but tape 3 containing the restart data must be present. This tape is written whenever IPUNCH = 0.

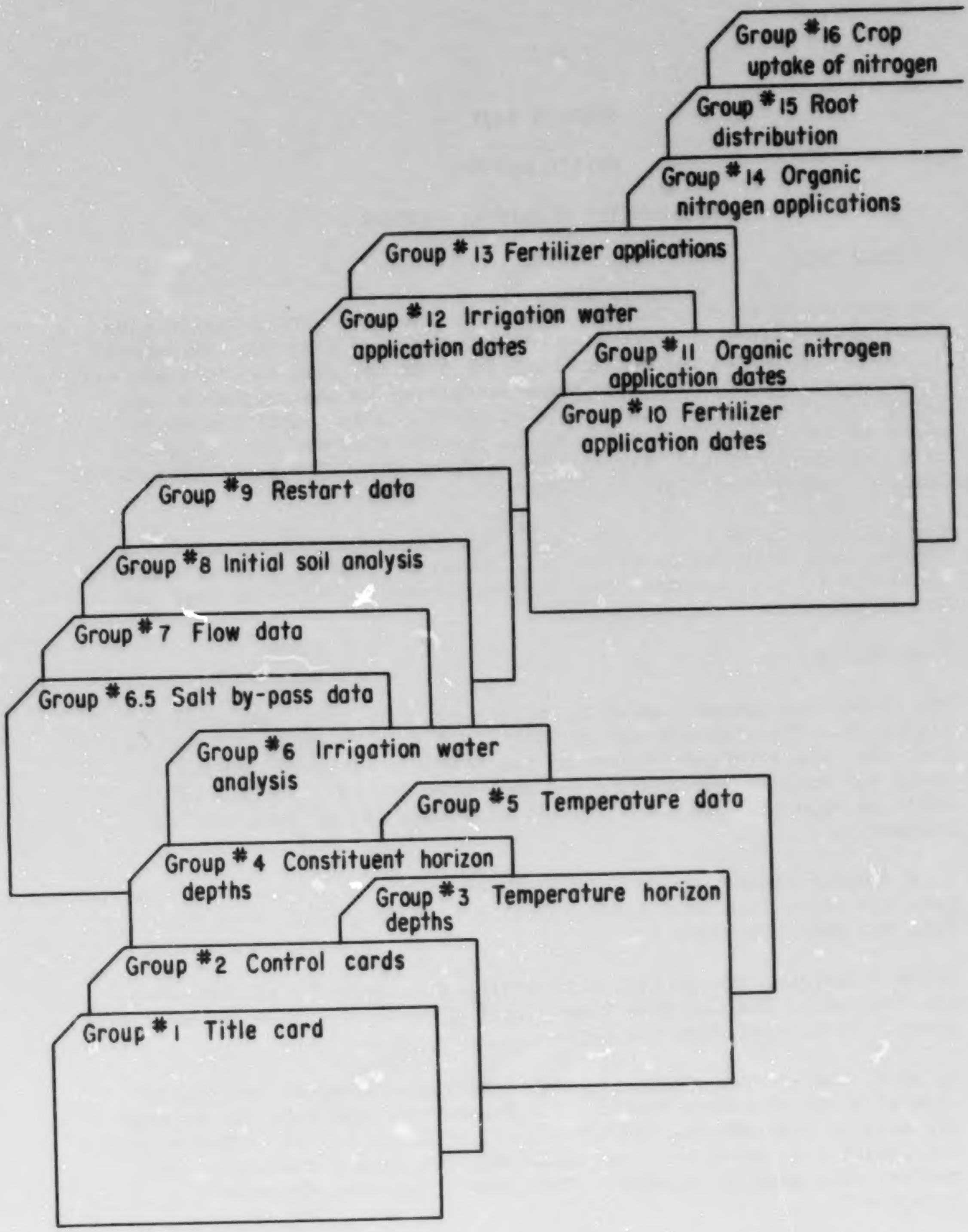

Group #16 Crop uptake of nitrogen
Group #15 Root distribution
Group #14 Organic nitrogen applications
Group #13 Fertilizer applications
Group #12 Irrigation water application dates
Group #11 Organic nitrogen application dates
Group #10 Fertilizer application dates
Group #9 Restart data
Group #8 Initial soil analysis
Group #7 Flow data
Group #6.5 Salt by-pass data
Group #6 Irrigation water analysis
Group #5 Temperature data
Group #4 Constituent horizon depths
Group #3 Temperature horizon depths
Group #2 Control cards
Group #1 Title card

FIGURE 21. CARD GROUPS IN UNSATURATED CHEMISTRY SUBMODEL

CARD GROUP 1 - Title Card

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	TITLE	Any title desired on printed output.

CARD GROUP 2 - Control Cards

Column No.	Var type	Var name	Variable description
Card 1 of 3			
1- 5	R	DELX	Soil segment size (cm). See page 145 for details.
6-10	R	DELT	Time interval size (days) corresponding to intervals for moisture flow on tape 1.
11-15	x	-	Not used by program.
16-20	R	CH	Convergence criterion for nitrogen transformation subroutine. See page 145 for details. Suggested values are in the range 0.1 - 10.0 p/m nitrogen.
21-25	R	CH1	Convergence criterion for ion exchange subroutine. See page 145 for details. Suggested values are in the range 1×10^{-2} - 1×10^{-6} moles/liter.
26-30	R	AL	Shutoff criterion for nitrogen transformation subroutine. See page 145 for details. Suggested values are in the range 0.1 - 2.0 ug/soil segment/time step.
31-35	R	A2	Shutoff criterion for ion exchange subroutine. See page 146 for details. Suggested values are in the range 1.0 - 5.0 ug/soil segment/time step.
36-40	X	-	Not used by program.
41-45	R	PK	Fraction of total plant uptake of nitrogen as NO_3-N. A suggested value is 0.95. As NO_3^--N mass → 0.0 plant uptake of NO_3^--N → 0.0 regardless of plant uptake imposed on system.

Column No.	Var type	Var name	Variable description
46-50	R	PK1	Fraction of total plant uptake of nitrogen as NH_4-N. A suggested value is 0.05. Fraction as NO_3-N plus fraction as NH_4-H must equal unity. The same relationship for NO_3-N holds for NH_4-N uptake with respect to the zero mass boundary condition.
51-55	R	FACT	Plant-N uptake constant for use with consumptive use values (if used).
Card 2 of 3			
1- 5	I	LL	Starting day of run relative to time reference date (e.g., if reference date is January 15 and starting day for run is January 21, the relative starting day would be day 7).
6-10	I	MM	Termination day of run relative to time reference date.
11-15	I	O	Number of soil chemistry horizons (must be in range 1 to 9 inclusive).
16-20	I	CROP	If 1, consumptive use used to determine N-uptake by plants. If 2, reserved for future use. If 3, read plant N-uptake data from cards (see card groups 15 and 16).
21-25	I	TO	Number of temperature horizons (must be in range 1 to 4 inclusive).
26-30	I	NT	Number of weekly temperature data cards (must = 0 for NBYPAS = 1) (see group 5).
31-35	I	IPRINT	Print interval (days) for predicted soil chemistry data.
36-40	I	JPRINT	Time interval within a day on which the IPRINT and IMASS print options are to be activated.

Column No.	Var type	Var name	Variable description
41-45	I	INK	Write interval (days) for output to tape 2 (see section 3).
46-50	I	IRERUN	If 0, program is to be run from initial input deck. If 1, program is to be restarted from tape or restart deck.
51-55	I	IPUNCH	If 0, no restart data deck will be punched (a restart tape (No. 3) is written). If 1, a restart data deck will be punched.
56-60	I	IREADP	If 0, program is to be restarted from tape 3 or started from initial data. If 1, program is to be restarted from cards (see group 9).
61-65	I	ITEST	If 0, moisture flow data are read from tape 1. If 1, moisture flow data are read from cards (see group 7).
66-70	I	START	Reference date in reference month (e.g., March 21 would be STARTING DAY = 21). See below.
71-75	I	SMØNTH	Reference month. Month to which all starts of the program are referenced (e.g., if reference month is March, STARTING MONTH = 3).
76-80	I	YEAR	Year for this run (e.g., if this is the third year being run, YEAR = 3).
Card 3 of 3			
1- 5	I	ISTOP	Year when run terminates (e.g., if run is to terminate after 3 years and starts with year 3, ISTOP = 5).
6-10	I	IMASS	Print interval (days) for summary of nitrogen balance for system.

Column No.	Var type	Var name	Variable description
11-15	I	IPRINTI	If 1, basic control card data are printed. If 0, printing of above is suppressed.
16-20	I	IPRINTJ	If 1, input data are printed. If 0, printing of above is suppressed.
21-25	I	NBYPAS	If 0, nitrogen transformations are considered. If 1, nitrogen transformations are bypassed, salt reactions remain in model if SBYPAS = 0.
26-30	I	SBYPAS	If 0, salt reactions are considered. If 1, salt reactions are bypassed, nitrogen transformations remain in model if NBYPAS = 0.
31-35	I	IDYSTR	Starting day for run. If LL > IDYSTR, LL - IDYSTR Records are skipped on tapes.
36-40	I	IDYSTP	Stopping day for run (uses MM value if year = ISTOP).
41-45	I	INFIL2	Starting file on output tape 2 (used when making a restart on tape 2 containing previous files).
46-50	I	INFIL1	Starting file on input tape 1 (used when more than one year's data are to be inputed to flow calculations).
51-55	I	ICONT1	If = 1, a new set of water application dates is read in each year. Also, no records can be skipped on tape 1.
56-60	I	ICONT2	If = 1, no record skipping can occur on tape 2. Otherwise (LL - IDYSTR) records are skipped on tape 2 following file positioning.
61-65	I	IOP	If = 1, lime precipitation is checked in relation to available pore space. If = 0, option is bypassed.

Column No.	Var type	Var name	Variable description
65-70	I	IOPN	If = 1, transition-state nitrification subroutine used. If = 0, statistical nitrification equation. (If = 1, constants and one statement function must be inserted into subroutine NITR; details are listed in the subroutine as comments.)
71-75	I	IPC02	If = 1, user supplies pCO_2 valves used (see group 8). If = 0, program relates pCO_2 to soil moisture content.
75-80	I	IREK	If = 1, cation exchange coefficients for Ca-Na and Ca-Mg ion exchange are read from soils analysis data cards. If = 0, default values within program are used.

ADDITIONAL DETAILS FOR CARD GROUP 2

Soil Segment Size

Soil segment size (or DELX, see figure 1) must be in the range [depth (cm) to water table/(25 - 1)] $\le$ Soil Segment Size $\le$ the size (cm) of the largest chemistry or temperature horizon. Here the 25 refers to array size currently used in the program.

Converge1

This constant determines the accuracy of the nitrogen changes computed in subroutine TRNSFM. A smaller value will increase accuracy and program execution time.

Converge2

This constant determines the accuracy of mass changes in the system computed in subroutine XCHANGE. A smaller value will increase accuracy and program execution time.

Check1

This constant is used in subroutine CHK to determine if subroutine TRNSFM should be called for that time step or bypassed and the previously computed nitrogen changes used. If the rates of change for nitrogen are less than CHECK1, TRNSFM is bypassed. However, TRNSFM is called at least once each day to avoid possible "drift" in the calculations.

Check2

This constant is used in subroutine CHK to determine if subroutine XCHANGE should be called for that time step or bypassed, in which case previously computed changes due to ion exchange, etc., are set equal to zero. XCHANGE is called at least once each day.

CARD GROUP 3 - Temperature Horizon Depths (Omit if NBYPAS = 1)

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	R	THØR(J)	Depth (cm) from surface to bottom of first temperature horizon.
6-10*	R	THØR(J)	Depth (cm) from surface to bottom of second temperature horizon (if it exists). (J = subscript for each horizon.)

CARD GROUP 4 - Chemistry Horizon Depths

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	R	HØR(J)	Depth (cm) from surface to bottom of first chemistry horizon.
6-10**	R	HØR(J) (J+1)	Depth (cm) from surface to bottom of second chemistry horizon.*** (J = subscript for each horizon.)

---

* The program allows the inclusion of up to four temperature horizons. If included, the depths for numbers 3 and 4 would be punched in columns 11-15 and 16-20, respectively.

** The program allows inclusion of up to nine chemistry horizons. If included, the depths for numbers 3, 4, 5, 6, 7, 8, and 9 would be punched in columns 11-15, 16-20, 21-25, 26-30, 31-35, 36-40, 41-45, respectively.

*** If only one chemistry horizon is desired, only one need be included.

CARD GROUP 5 - Temperature Data (Omit if NBYPAS = 1)

Column No.	Var type	Var name	Variable description
Card 1 of NT*			
1- 2			Card indentification (not read by program).
3-10	R	TT(K)	Weekly temperature (°C) for uppermost (first) temperature horizon.
10-20**	R	TT(K) (K+1)	Weekly temperature (°C) for second temperature horizon.*** (K = subscript for weekly temperatures.)

CARD GROUP 6 - Irrigation Water Analysis

Card 1 of 1

Column No.	Var type	Var name	Variable description
			(All units in meq/L of the species shown.)
1- 5	R	ANH3(1)	NH_4^+
6-10	R	AN03(1)	NO_3^-
11-15	R	CA(1)	Ca^{++}
16-20	R	ANA(1)	Na^+
21-25	R	AMG(1)	Mg^{++}
26-30	R	HC03(1)	HCO_3^-

---

* NT is the number of temperature data cards. Each card contains weekly data for all temperature horizons.

** The program allows inclusion of up to four temperature horizons. If included, temperature data for horizons 3 and 4 would be punched in columns 21-30 and 31-40, respectively.

*** If only one temperature horizon is desired, only one need be included.

Note: The first temperature data should correspond to the week beginning with the reference data (see Section 5 for exceptions).

Column No.	Var type	Var name	Variable description
31-35	R	CL(1)	Cl^-
36-40	R	CØ3(1)	$CO^=_3$
41-45	R	SØ4(1)	$SO^=_4$

Note: All irrigation water is assumed to have same analysis.

CARD GROUP 6.5 - (Needed if SBYPAS = 1, and NBYPAS = 0)

Card 1 of Q-1

Column No.	Var type	Var name	Variable description
1- 5	R	SERATIØ(J)	Fraction of total NH_4^+ which is soluble NH_4^+.
6-10	R	U(J)	Ionic strength - needed only when IOPN = 1.
11-15	R	ACTCA(J)	Ca^{++} activity - needed only when IOPN = 1.

CARD GROUP 7 - Moisture Flow Data (Needed only if ITEST = 1; if ITEST = 0, tape 1 is used)

Card 1 of NS*

Column No.	Var type	Var name	Variable description
1-10	R	CMH2Ø1(J)	Volume of water in segment (cc).
11-20	R	MØISIN(J)	Water movement across upper boundary of segment (cc/time step).**
21-30	R	MØISØUT(J)	Water movement across lower boundary of segment (cc/time step).**
31-40	R	TEN(J)	Average moisture tension (cm) over time step (tensions shown as negative).
41-50	R	U(J)	Plant water uptake (cm/time step/soil segment).

---

* NS is the number of moisture flow data cards. There must be a card for each segment including No. 1. For details in computing NS, see page ___.

** Positive sign for downward flow, negative for upward flow.

CARD GROUP 8 - Initial Soil Analysis (Omit if IRERUN = 1)

Column No.	Var type	Var name	Variable description
Card 1 of NC*			
			(Units in meq/L of species shown unless otherwise noted.)
1- 5	R	ANH3(1)	NH_4^+ (soluble form).
6-10	R	AN03(1)	NO_3^-.
11-15	R	UREA(1)	UREA.
16-20	R	CA(1)	Ca^{++}
21-25	R	ANA(1)	Na^+.
26-30	R	AMG(1)	Mg^{++}.
31-35	R	HC03(1)	HCO_3^-.
36-40	R	CL(1)	Cl^-.
41-45	R	C03(1)	$CO_3^=$.
46-50	R	S04(1)	$SO_4^=$.
51-55	R	EC(1)	Exchange capacity (meq/100 gm soil).
56-60	R	XX5(1)	Gypsum (meq/100 gm) soil.
61-65	R	CAL(1)	If 0.0, no lime is present in soil. If 1.0, lime is present in soil.
66-70	R	BD(1)	Bulk density (gm/cc of soil).
71-75	R	SAMT(1)	Soil organic nitrogen (ug/gm soil).
76-80	R	CN1(1)	Carbon-nitrogen ratio of soil organic matter (e.g., 40:1 would be punched as a 40.0).

---

* NC is the number of chemistry horizons.

Column No.	Var type	Var name	Variable description	
Card 2 of Set				
1- 5	R	XTRCT(1)	Gm water/gm soil in soil extract.	
6-15	R	PC02(1)	CO_2 partial pressure in atmospheres (needed only if $IPC0_2 = 1$)	
16-20	R	AKCS(1)	Ca-Na exchange coefficient.	needed only if IREK = 1
21-25	R	AKCM(1)	Ca-Mg exchange coefficient.	

CARD GROUP 9 - Restart Data

This data group is punched by the program during a previous run. See page ___ for details. The punch/read format is (4I5/, (6E13.5/6E13.5/6E13.5/6E13.5/E13.5)).

CARD GROUP 10 - Fertilizer Application Dates

Card 1 of 1*

Column No.	Var type	Var name	Variable description
1- 5	I	IT0T	Number of fertilizer applications.
6-10	I	IADD(K)	First application day relative to reference starting date.
11-15**	I	IADD(K) (K+1)	Second application day relative to reference starting date.

CARD GROUP 11 - Organic Nitrogen Application Dates (Omit if NBYPAS = 1)

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	I	JT0T	Number of organic nitrogen applications.
6-10	I	I0RNAP(K)	First organic nitrogen application day relative to reference date.

---

* A second card may be used if needed (i.e., if the number of applications exceeds 15, in which case the I5 format still applies).

** The program allows inclusion of up to 25 fertilizer application dates. The same format, I5, is used for any additional dates desired.

Column No.	Var type	Var name	Variable description
11-15*	I	IORNAP(K) (K+1)	Second organic nitrogen application day relative to reference date.

CARD GROUP 12 - Irrigation Water Application Dates

Card 1 of 1**

Column No.	Var type	Var name	Variable description
1- 5	I	IRTOT	Number of irrigations.
6-10	I	IRR(K)	First irrigation day relative to reference date.
11-15***	I	IRR(K) (K+1)	Second irrigation day relative to reference date.

CARD GROUP 13 - Fertilizer Applications

Card 1 of NF****

Column No.	Var type	Var name	Variable description
			All units in lbs/acre of species shown unless otherwise labeled.
1- 5	R	FERT(1)	Depth (cm) of a uniform fertilizer application. If = 0.0, a surface application is indicated.
6-10	R	FERT(2)	NH_4^+.
11-15	R	FERT(3)	NO_3^-.
16-20	R	FERT(4)	Urea ($NH_2\text{-}\dot{C}\text{-}NH_2$).

---

* The program allows inclusion of up to organic nitrogen application dates. If included, application dates for applications 3, 4, and 5 would be punched in columns 16-20, 21-25, and 26-30, respectively.

** A second data card may be needed if more than 15 irrigation dates are used.

*** The program allows inclusion of up to 25 irrigation dates. If included, applications 3-25 would follow the same I5 format.

**** NF is the number of fertilizer applications. The maximum number allowed in the program is 25.

Column No.	Var type	Var name	Variable description
21-25	R	FERT(5)	Ca^{++}.
26-30	R	FERT(6)	$SO_4^{=}$.
31-35	R	FERT(7)	$CO_3^{=}$.

CARD GROUP 14 - Organic Nitrogen Applications (Omit if NBYPAS = 1)

Card 1 of NO*

Column No.	Var type	Var name	Variable description
1- 5	R	ØFERT(1)	Depth (cm) of uniform organic nitrogen applications (surface applications are not allowed).
6-10	R	ØFERT(2)	Carbon:nitrogen ratio of organic matter added (containing the organic N) (e.g., 40:1 would be punched as a 40.0).
11-15	R	ØFERT(3)	Organic nitrogen added (lbs/acre) as oven dry weight.

CARD GROUP 15 - Plant Root Distribution

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	KP2(1)	Fraction (decimal) of plant roots from 0-1 foot depth.
11-20	R	KP2(2)	Fraction from 1 foot to 2 feet.
21-30	R	KP2(3)	Fraction from 2 feet to 3 feet.
31-40	R	KP2(4)	Fraction from 3 feet to 4 feet.
41-50	R	KP2(5)	Fraction from 4 feet to 5 feet.
51-60	R	KP2(6)	Fractions > 5 feet.

---

* NO is the number of organic matter applications. The maximum number allowed in the program is 5.

Note: Plant root distribution is independent of time. If roots do not extend to 5 feet, use zero fractions for roots below their deepest extension.

CARD GROUP 16 - Plant Uptake of Nitrogen

Column No.	Var type	Var name	Variable description
Card 1 of NP*			
1-10	X	-	Space for card identification.
11-20	R	UPTK(K)	Plant uptake of nitrogen (lbs-N/acre/semimonthly). (K = subscript for each semimonthly period.)

TAPE INPUTS

Tape input to the Biological-Chemical program consists of two optional tapes written in binary. Tape 1 contains moisture flow data written by program INTFACE. An alternate procedure is to input moisture data on cards. In this case a single set of constant moisture data is read. Tape 3 may be read to restart the program after a previous run. This tape is always written at the conclusion of a run. Unless a magnetic tape is equipped to tape unit 3, the binary data are written on a disk or drum. Disk or drum data may be lost at the conclusion of a run. The alternative to a restart from tape 3 is a restart from data cards.

TAPE 1

Field No.	Var type	Var name	Variable description
Logical Record			
1 of NR			
1	I	I1	Reserved for future use.

---

* NP is the number of semimonthly** plant uptake data cards. The program requires that 24 cards be present, even if not all of them are used.

** Semimonthly means the period from the 1st day through the 15th day or from the 16th day through the last day of the month. The 1st data card begins with the semimonthly period containing the reference starting date (see page 143). Remaining data cards contain data for consecutive semimonthly periods taken chronologically from the 1st.

Field No.	Var type	Var name	Variable description
2	I	I2	Reserved for future use.
3	I	I3	Reserved for future use.
4	I	I3	Reserved for future use.
5	R	CMH2Ø1(J)	Current column of water (cc) in Jth* soil segment.
6	R	MØISIN(J)	Moisture flow (cc/time step) into the Jth soil segment.
7	R	MØISØUT(J)	Moisture flow (cc/time step) from the Jth soil segment.
8	R	TEN(J)	Average current moisture tension (cm H_2O) for Jth segment (sign - ±).
9	R	U(J)	Consumptive use (cc/time step) for the Jth segment.

TAPE 3

Logical Record

1 of 1

1	I	ICØUNT	Restart counter for plant uptake data.
2	I	INFERTIN	Restart counter for fertilizer application data.
3	I	NØRGRIN	Restart counter for organic matter applications data.
4	I	NTEMPIN	Restart counter for temperature data.

---

* This sequence of nine fields is repeated Q times per logical record. Q is the total number of segments. Its value may be computed using the algorithm outlined on page 155. NR is the number time steps for which data are written on tape 1.

Field No.	Var type	Var name	Variable description
5*	R	ANH3(J)	µg of NH_4-N contained in Jth** segment.
6	R	ANO3(J)	µg of NO_3-N contained in Jth segment.
7	R	UREA(J)	µg of Urea-N contained in Jth segment.
8	R	CA(J)	µg of Ca^{++} contained in Jth segment.
9	R	ANA(J)	µg of Na^{+} contained in Jth segment.
10	R	AMG(J)	µg of Mg^{++} contained in Jth segment.
11	R	HC03(J)	µg of HCO_3^{-} contained in Jth segment.
12	R	CL(J)	µg of Cl^{-} contained in Jth segment.
13	R	C03(J)	µg of $CO_3^{=}$ contained in Jth segment.
14	R	S04(J)	µg of $SO_4^{=}$ contained in Jth segment.
15	R	EC(J)	Exchange capacity of Jth segment.
16	R	XX5(J)	Gypsum concentration in Jth segment (moles/L).
17	R	CAL(J)	If 1.0, lime is present in Jth segment. If 0.0, lime is not present in Jth segment.
18	R	BD(J)	Soil bulk density of Jth segment.
19	R	SAMT(J)	µg of organic matter just applied to Jth segment.
20	R	CN1(J)	C:N ratio of organic matter in Jth segment.
21	R	ORN(J)	µg of organic-N in Jth segment.

---

* Fields No. 5-33 inclusive are repeated Q times in each logical record. Q is the number of segments and may be determined using the following algorithm: Q = DEPTH to W.T./DELX + 1.1, where any fraction is dropped in determining the final value for Q.

** The segments begin with J = 1 and end with J = Q.

22	R	RN(J)	Residue nitrogen in Jth segment (μg/g).
23	R	RC(J)	Residue carbon in Jth segment (μg/g).
24	R	E5(J)	Exchangeable Ca^{++} in Jth segment (moles/g).
25	R	C5(J)	Exchangeable Mg^{++} in Jth segment (moles/g).
26	R	SA5(J)	Exchangeable N^{+} in Jth segment (moles/g).
27	R	CAS0(J)	Undissociated $CaSO_4$ in Jth segment (moles/L).
28	R	AGS0(J)	Undissociated $MgSO_4$ in Jth segment (moles/L).
29	R	BNH4(J)	Exchangeable $NH^{+}{}_4$ in Jth segment (moles/g).
30	R	XTRCT(J)	Ratio of water/soil in the extract for Jth segment.
31	R	ANETLIM(J)	Current amount of pore space occupied by lime in Jth segment.
32	R	AZE(J)	A value proportional to K^1 and associated with lime precipitation-dissolution and CO_2 partial pressures. Value is for Jth segment.
33	I	IIK(J)	Current lime indicator for Jth segment.

CARD OUTPUTS

Card output from the program consists of data needed to restart a run after a previous execution. This card deck is generated only if the proper control card request has been made (see Card Group 2). No card deck is punched if a program run terminates abnormally (e.g., a fatal error occurs). A discussion of the punch format is presented in Section 1, under card group 9. See tape 3, page 154, for variable descriptions.

TAPE OUTPUTS

Tape output from the Biological-Chemical program consists of one binary (tape 2) and one binary (tape 3) file. Tape 2 contains the soil leachate data. This may serve as input to routines which consider saturated flow and saturated chemistry. Tape 3 contains restart data which may be read into the program to restart a previously terminated run.

TAPE 2

Logical Record	Var type	Var name	Variable description
1 of NR			
1	I	YEAR	Year number.
2	I	IDAY	Day number.
3	R	SUMOUT	Water leached since start of run (cc/cm^2).
4	R	DELN	Water leached since previous record was written (cc/cm^2).
5	R	AMT(1)	NO_3^-N leached since start of run (μg/cm^2).
6	R	DEL(1)	NO_3^-N leached since previous record was written (μg/cm^2).
7	R	AMT(2)	NH_4^-N leached since start of run (μg/cm^2).
8	R	DEL(2)	NH_4^-N leached since previous record was written (μg/cm^2).
9	R	AMT(3)	Urea-N leached since start of run (μg/cm^2).
10	R	DEL(3)	Urea-N leached since previous record was written (μg/cm^2).
11	R	AMT(4)	Ca^{++} leached since start of run (μg/cm^2).
12	R	DEL(4)	Ca^{++} leached since previous record was written (μg/cm^2).
13	R	AMT(5)	Na^+ leached since start of run (μg/cm^2).
14	R	DEL(5)	Na^+ leached since previous record was written (μg/cm^2).

Logical Record	Var type	Var name	Variable description
15	R	AMT(6)	Mg^{++} leached since start of run (μg/cm^2).
16	R	DEL(6)	Mg^{++} leached since previous record was written (μg/cm^2).
17	R	AMT(7)	HCO^-_3 leached since start of run (μg/cm^2).
18	R	DEL(7)	HCO^-_3 leached since previous record was written (μg/cm^2).
19	R	AMT(8)	Cl^- leached since start of run (μg/cm^2).
20	R	DEL(8)	Cl^- leached since previous record was written (μg/cm^2).
21	R	AMT(9)	$CO^=_3$ leached since start of run (μg/cm^2).
22	R	DEL(9)	$CO^=_3$ leached since previous record was written (μg/cm^2).
23	R	AMT(10)	$SO^=_4$ leached since start of run (μg/cm^2).
24	R	DEL(10)	$SO^=_4$ leached since previous record was written (μg/cm^2).

NR is the number of records written on tape 2. The write interval (i.e., time between write operations is specified by the user (see card group 2)).

HINTS ON PROGRAM USE

a. Be sure core is set to zero before program is loaded.

b. The program can be operated very easily from a time-share terminal. This should be done when possible.

c. Subroutines will not load in a random order due to varying sizes of common blocks. See suggested load sequence on page 160.

d. An end-of-file is written on tape 2 at the conclusion of a run and at the end of each year. This means that output from several runs and/or years may be stored as separate files on the same or individual tapes.

e. A run which exits due to a time limit or other error will not produce a restart deck or tape.

f. The number of temperature cards may be reduced when making a restart run by altering the value of the number contained in Field No. 4 of the restart deck or tape. The number placed there by the program is the number of cards or records to skip in order to locate the correct temperature data card.

g. If no plant uptake of N is required, set CROP equal to 1 and leave columns 51-55 of the first control card blank. In this case, CARD GROUP 16 may be omitted from the deck.

h. When using the IOPN = 1 option, values for certain parameters, plus a statement function must be inserted into NITR.

i. The program can be operated with either the salt portion or the nitrogen portion bypassed.

j. The program can be operated so that certain months of the year are bypassed.

k. Be sure to check the input data carefully. The program may run and terminate normally with bad data.

l. The mass balance check on nitrogen is an important item. Any large errors here indicate something has gone wrong.

m. If a run should "blow up" first check your card input data and then any data being read from tapes.

n. An average execution time on a CDC CYBER 74-28 is about 0.4 second/day using 11 segments and 0.1 day time steps.

SUGGESTED LOAD SEQUENCE

Load order	Routine
1	MAIN
2	COMBINE
3	TRNSFM
4	XCHANGE
5	EQEXCH
6	NITR
7	NEGN
8	SALTBP
9	EXECUTE
10	MCHECK
11	OUTPT
12	DAY
13	IDAY
14	THEDATE
15	UNITS 1
16	FL
17	PRNT
18	WGT
19	UPTAKE
20	CHK
21	TEMP
22	QROTP
23	QTRAN
24	COMP
25	PHCALC
26	SKIP

SECTION XIV

USER'S MANUAL

SATURATED FLOW PROGRAM

INTRODUCTION

This program was designed to predict the average or steady-state response of a subsurface drainage system to deep percolation inputs. The drainage system consists of parallel, equally spaced, tile drains. Either the average annual deep percolation rate for uniform seepage (boundary condition 1, BC1) or the average annual water table position for the ponded water case (boundary condition 2, BC2) provide the flow inputs. In particular, this program was developed as part of an irrigation return flow water quality model.

For computation purposes, the saturated aquifer is divided into a number of individual stream tubes. Discharge rates through each tube are identical. In addition, a node concept is employed to permit the determination of each tube's location. Theoretical techniques and details are contained in the program description.

Output includes the position of the water table (BC2) or the seepage distribution between drains (BC1), location of the stream tubes, time of travel down each tube, pore volume of each tube, and the steady-state discharge from the drains. Pore volumes are intended for input to the saturated chemistry portion of the water quality model while the drain discharge and travel times are input to the drain effluent prediction portion.

UNIT NUMBERS

Two input-output devices are referenced by the program:

Unit designation	Unit description or purpose
5	The common input tape or unit (CIT). It is the computer system's standard input device.
6	The common output tape or unit (COT). It is the computer system's standard output device.

In addition, the program uses an internal scratch or peripheral storage unit (unit 8) which is assigned to disk. Data defining the streamline locations are written without format (binary) if a cathode ray tube (CRT) plot of the streamlines using a distorted vertical scale is requested.

DATA DECK STRUCTURE

Seven input cards are required for BC1 and eight for BC2 as shown in Figure 22. Certain cards are common to both boundary conditions. Referring to the card numbers of Figure 22, the input deck for BC1 consists of cards 1, 2, 3, 4A, 5A, 7, and 8 while for BC2 cards 1, 2, 3, 4, 5, 6, 7, and 8 are used.

CARD GROUP 1 - Title Information

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	TITLE	An 80-character alphanumeric title used to identify all printed and plotted output. If this title is desired to be centered on output, it must be centered on the card.

CARD GROUP 2 - Problem Selection

Card 1 of 1			
1-40 (40I1 Format)	I	IPRØB(I)	A control array which calls the proper overlay for execution. Individual programs in the water quality model were originally designed for inclusion in an overlay system. Presently (March, 1973), only the saturated flow and drain effluent portions are included. When IPRØB(I) is set to 1, the Ith overlay is called. Thus IPRØB(1) = 1, call the saturated flow routine. IPRØB(2) = 1, call the drain effluent routine. On output, values of IRPØB(I) are listed as IØC values under the heading - PROBLEM CONTROL INFORMATION FOR MAIN PROGRAM.

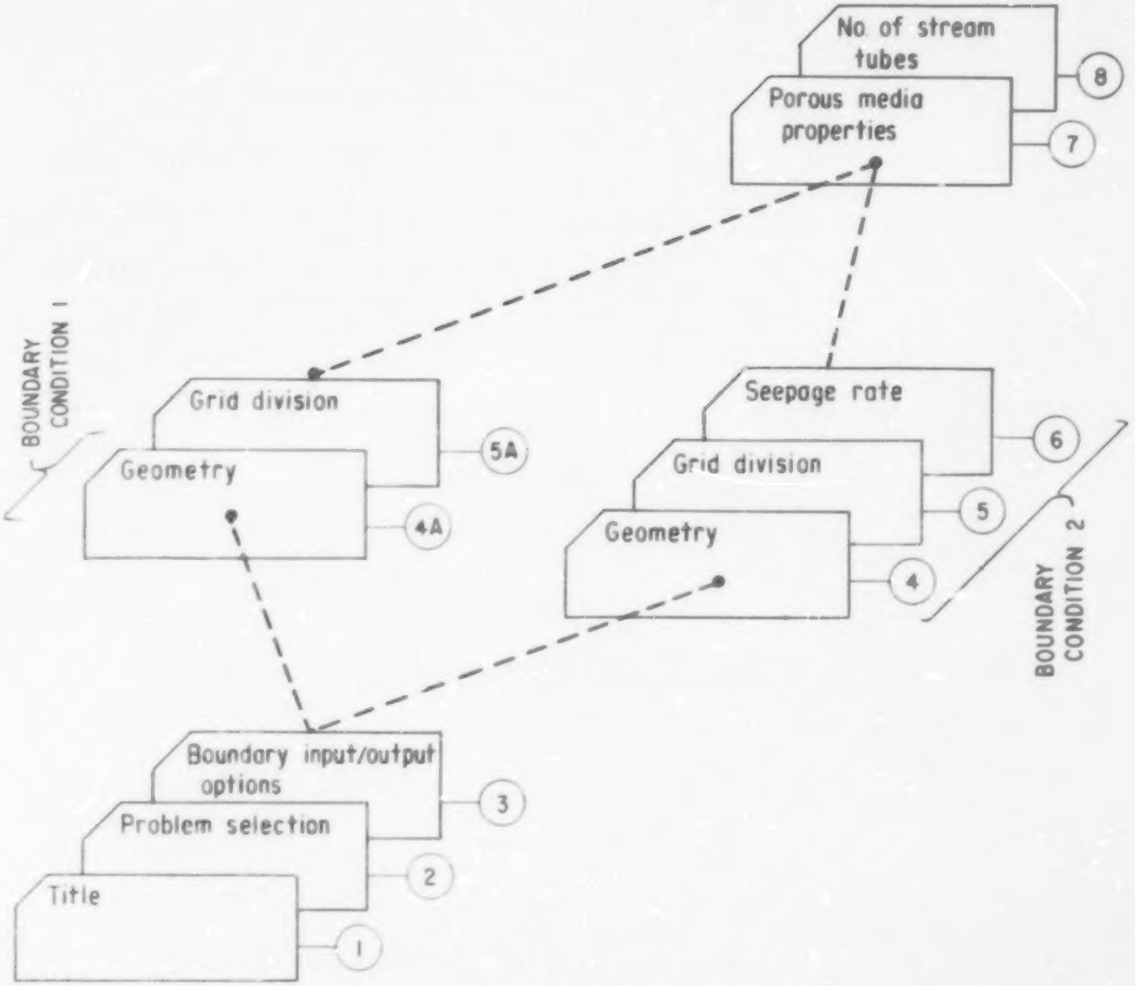
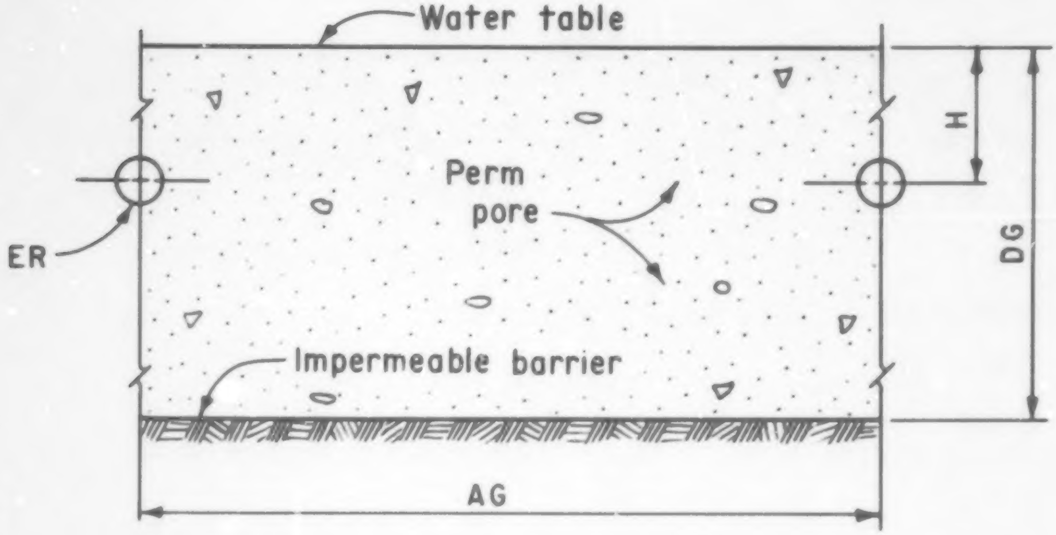
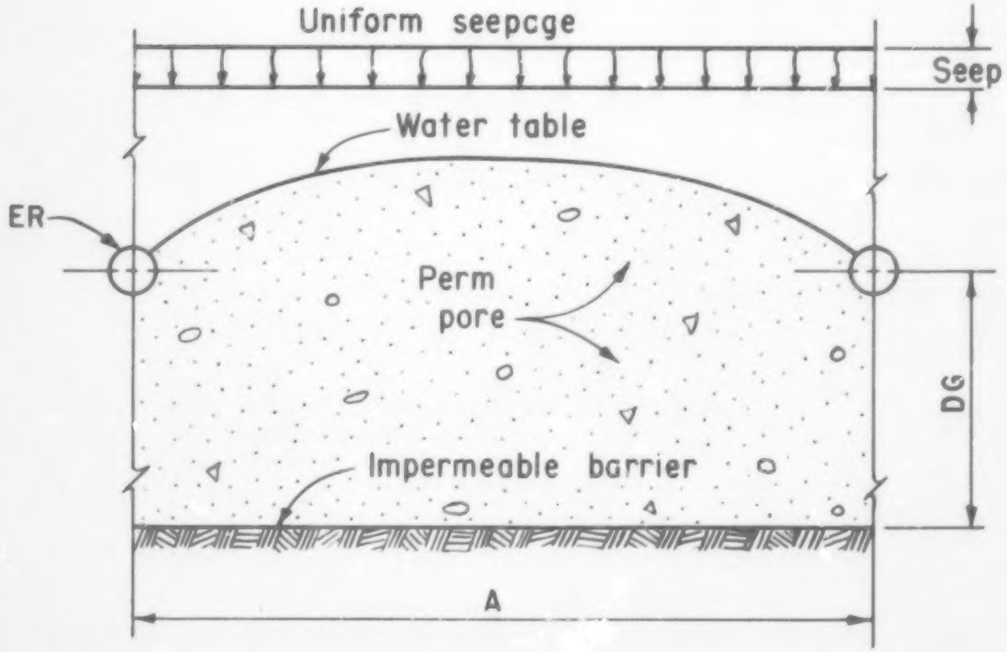

No. of stream tubes
8
Porous media properties
7
BOUNDARY CONDITION 1
Grid division
5A
Geometry
4A
Seepage rate
6
Grid division
5
Geometry
4
BOUNDARY CONDITION 2
Boundary input/output options
3
Problem selection
2
Title
1

FIGURE 22 DATA DECK STRUCTURE-SATURATED FLOW SUBMODEL

Column No.	Var type	Var name	Variable description
CARD GROUP 3 - Boundary Condition and Input/Output Options			
Card 1 of 1			
1-10	I	IBC	Boundary condition selector. IBC = 1, selects the ponded water case. IBC = 2, selects the uniform seepage case. IBC = any other value will produce questionable results. (There is no check for a legitimate boundary condition number.) The boundary condition number is incorporated into a subtitle on output.
11-50 (40I1 Format)	I	IOC(I)	IOC(I) = An input/output option array used to select printed and plotted output. (See Input/Output Options.)
CARD GROUP 4 - Geometry for BC2 (see Figure 23)			
Card 1 of 2			
1-10	R	DG	Distance from horizontal centerline of drain to the impermeable barrier (feet).
11-20	R	A	Drain spacing (feet).
21-30	R	ER	Effective drain radius (feet).
Card 2 of 2			Geometry for BC1 (see Figure 23).
1-10	R	DG	Distance from horizontal centerline of drain to the impermeable barrier (feet).
11-20	R	AG	Drain spacing (feet).


Water table
H
DG
Perm
pore
ER
Impermeable barrier
AG

(a) BOUNDARY CONDITION 1


Uniform seepage
Seep
Water table
ER
Perm
pore
DG
Impermeable barrier
A

(b) BOUNDARY CONDITION 2

FIGURE 23. BOUNDARY CONDITIONS-SATURATED FLOW SUBMODEL

Column No.	Var type	Var name	Variable description
21-30	R	H	Vertical distance from the water table to the horizontal centerline of the drain (feet).
31-40	R	ER	Effective drain radius (feet).

CARD GROUP 5 - Grid Division Data for BC2

Card 1 of 2

Column No.	Var type	Var name	Variable description
1- 5	I	M1	The number of primary grids to be subdivided in the horizontal direction.
6-10	I	N1	The number of primary grids to be subdivided in the vertical direction.
11-15	I	L	The number of subdivisions of the primary grid.
16-25	R	HG	The nominal size of the primary grid (feet).
Card 2 of 2			Grid division data for BC1.
See above		M1 N1 L	Same description as in card 5.

CARD GROUP 6 - Seepage Rate for BC2

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	SEEP	Average annual seepage or deep percolation rate between the drains ($feet^3/feet^2$/year or feet/year).

CARD GROUP 7 - Porous Media Properties

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	PERM	Coefficient of permeability (feet/year).

Column No.	Var type	Var name	Variable description
11-20	R	PØRE	Total porosity expressed as a decimal (feet^3/feet^3 or dimensionless).

CARD GROUP 8 - Number of Stream Tubes

Card 1 of 1

1-10	I	NST	The number of stream tubes or streamlines used to define flow from one side of the drain.

STANDARD OUTPUT

Output includes results printed on unit 6 and plotted on a cathode ray tube (CRT) plotter*. Certain portions of the printed output are standard while others are optional. All CRT plots are optional. The next section describes the optional output.

Standard printed output common to both boundary conditions includes:

a. input/output options (IØC(I));

b. boundary condition number;

c. given and modified aquifer geometry;

d. porous media properties;

e. grid division data;

f. number of stream tubes;

g. flow into the drain per foot of length;

h. travel time down each tube;

i. pore volume contained in each tube;

j. error messages, if any.

In addition, standard output for BC1 includes the average seepage rates between adjacent streamlines as well as the average rate between drains. For BC2, additional output includes the ratio of the seepage rate to the permeability and the maximum and minimum water table position at 50, equally spaced points between the drain and the midpoint between drains.

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* Plotter subroutines are not included in the model version included in this Volume.

INPUT/OUTPUT OPTIONS

Individual output options are selected by setting the appropriate IOC(I) value to 1. Options are bypassed if the value is left blank or set to 0. Available options are identical for both boundary conditions with the exception of IOC(28) which only applies to BC1. The descriptions below may be more meaningful if reference is made to the computational approach described in the program description. It should be noted that most of the print options are intended for debugging use.

I	Option
1	Select all print options. All individual print options (I=3 through 25) are set to 1 by this option.
2	Select all CRT plot options.* All individual plot options (I=26 through 40) are set to 1 by this option.
3-25	Reserved for individual print options.
3	Print required values of streamlines used to define the flow system.
4	Print coordinates of all nodes.
5	Print coordinates and the stream function at all nodes that are required to define the system.
6	Print coordinates and corresponding potentials for all points locating the required streamlines after horizontal interpolation.
7	Print coordinates and corresponding stream function for all nodes in each vertical column of nodes.
8	Print coordinates and corresponding potentials for all points locating the required streamlines after horizontal and vertical interpolation.
9	Print coordinates and corresponding potentials for all points defining a streamline before sorting (raw data).
10	Print coordinates and corresponding potentials for all points defining a streamline after sorting (sorted data).

---

* Not available in this version of the model.

I	Option
11	Print coordinates and corresponding potentials for all points defining a streamline after the sorted data have been modified to exclude points within the drain and a point added on the drain perimeter (modified data).
12-25	Options are not presently used (March, 1973).
26-40	Reserved for individual plot options (not available).

GRID DIVISION AND GEOMETRY MODIFICATION

Application of the node concept based on input of grid division data has been explained in the program description. Given (input) dimensions of the aquifer are automatically adjusted by the program so that the aquifer geometry is a multiple of the primary or coarse grid size.

For BC1, the depth from the water table to the horizontal centerline of the drain, H, is used for the coarse grid size. Both the depth to barrier, DG, and drain spacing, AG, are modified. Since the user has no control over the coarse grid size, the effect of geometry adjustments is of interest. The computed drain discharge is a prime indicator of this effect. Figure 24 presents the effect on the dimensionless flow parameter of various dimensionless geometry parameters:

a. Ratio of drain depth to barrier depth.

b. Ratio of drain spacing to drain depth.

c. Ratio of effective drain radius to drain depth.

For normal drainage situations, the solution is seen to be relatively insensitive to changes in the aquifer geometry.

For BC2, the nominal size of the primary grid, HG, is input. Because drain discharge is directly proportional to the drain spacing, A, HG is adjusted so A is a multiple of the adjusted size. The barrier depth, DG, is then modified. If HG is judiciously chosen, or if it is made small relative to DG, adjustments can be minimized.

LIMITATIONS AND ERROR MESSAGES

The program description lists limitations on the size of the problem that can be analyzed. They are repeated here:

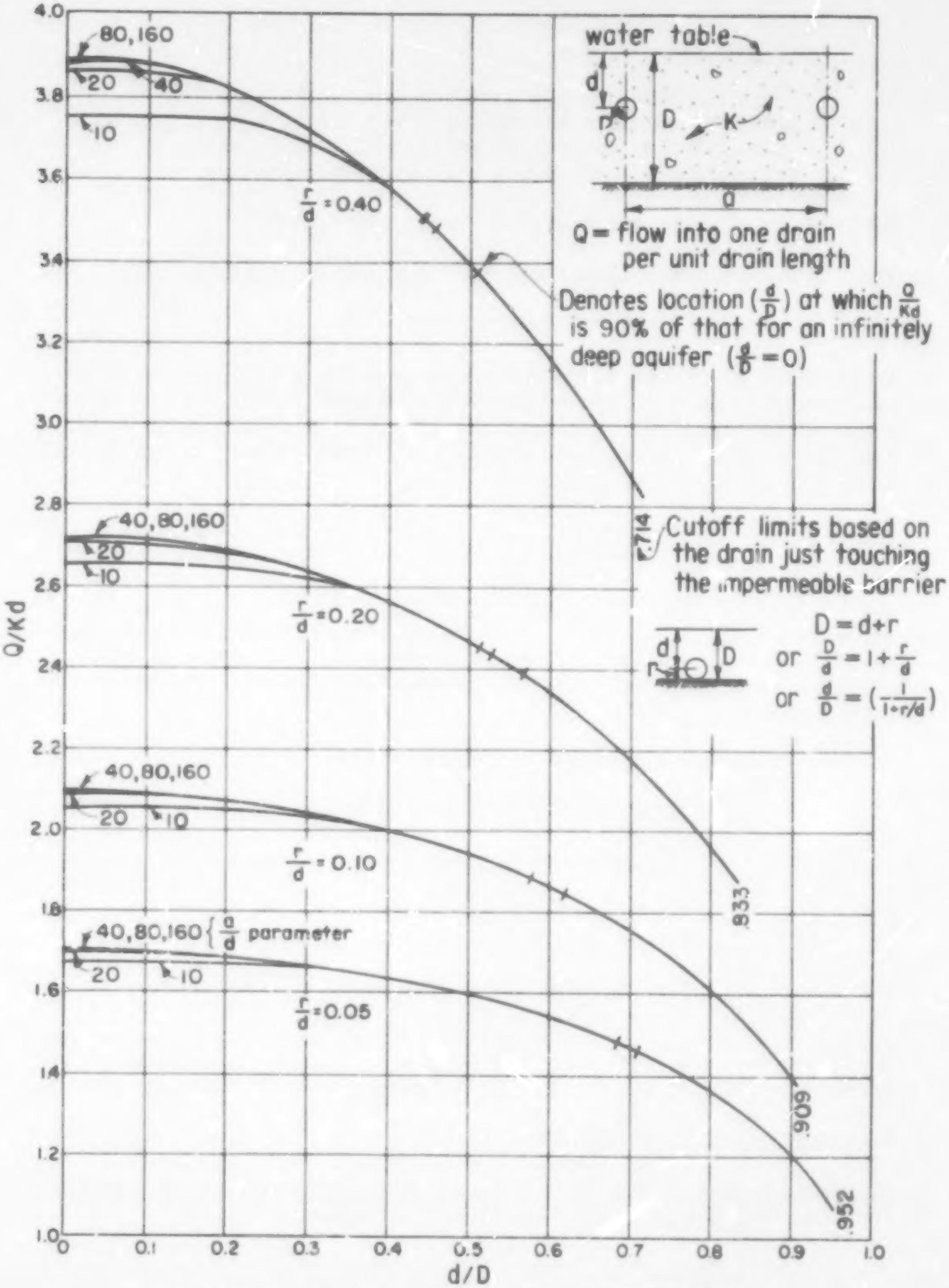


FIGURE 24. DIMENSIONLESS FLOW
CIRCULAR TILE DRAINS BELOW HORIZONTAL WATER TABLE

a. Maximum total number of nodes is 3,000 and the maximum number in any vertical grid line is 400. Since these numbers depend on the aquifer geometry and grid subdivision data, the user has direct control. Equations to check these numbers prior to a run are given in the next section.

b. Maximum number of interpolated points defining the streamlines is 3,000. The user has indirect control on this number since it depends on the number of nodes and streamlines, as well as the aquifer geometry and boundary conditions. If this situation is encountered, a coarser grid can be used or the number of streamlines reduced.

c. Maximum number of stream tubes is 20. If more are specified, the program notes the condition, reduces the number to 20, and continues. It should be noted that other programs in the water quality model can only accept information for 10 tubes (i.e., SATCHEM and DE0200).

d. Maximum seepage rate for BC2 must be less than the permeability. This restriction is imposed by the physical nature of the problem since the ultimate steady state would be the ponded water case.

Error messages are generated if the above limitations are violated. In addition, failure of the infinite series for the solution constants, stream functions, and potential functions produce error messages. A list of all error messages is contained in the Appendix. Suggested courses of action when errors do occur are included.

EQUATIONS FOR NUMBER OF NODES

If the user has specified subdivision information which causes more than 3,000 nodes to be computed, an error message is generated and execution is terminated. Should there be any suspicion that this situation might prevail, the equations given below may be used to avoid possibly unproductive runs.

For BC1, the equation is

$$\begin{aligned} NT = {} & MP+(MP)(NP)+NP+(M1+N1)(L-1) \\ & +(M1)(N1)(L^2-1)+3L(2L+1) \end{aligned} \qquad [50]$$

where NT is the total number of nodes (excludes origin);
MP is the number of primary grid elements in the horizontal direction;
NP is the number of primary grid elements in the vertical direction; and
M1, N1, L are as described in the Data Deck section.

For BC2, the equation is

$$NT = MP+(MP)(NP)+NP+(M1+N1)(L-1) + (M1)(N1)(L^2-1)+L(3L+2) \quad [51]$$

where all terms are defined as before.

The determination of MP and NP requires use of the methods employed by the program in modifying the aquifer geometry. For BC1, the following procedure is followed:

a. Compute DG/H and AG/(2H).

b. Then NP is the integer part of DG/H if the decimal part is ≤0.5. MP is the integer part of DG/H increased by 1 if the decimal part is >0.5.

c. Similarly MP is the integer part of AG/(2H) is the decimal part is <0.5.
MP is the integer part of AG/(2H) increased by 1 if the decimal part is >0.5.

As an example, if DG = 28., AG = 150., and H = 10., then DG/H = 2.8, AG/(2H) = 7.5 from which NP = 3 and MP = 7.

For BC2, the following procedure is used:

a. Compute A/(2HG).

b. Then MP is the integer part of A/(2HG) if the decimal part is <0.5.
MP is the integer part of A/(2HG) increased by 1 if the decimal part is >0.5.

c. The modified primary grid size is H = A/(2MP).

d. Compute DG/H.

e. Then NP is the integer part of DG/H if the decimal part is <0.5.
NP is the integer part of DG/H increased by 1 if the decimal part is >0.5.

As an example, if DG = 28., A = 150., and HG = 10., then A/(2HG) = 7.5, MP = 7, and H = 150/14 = 10.71. Computing DG/H = 2.6, NP = 3.

An additional restraint on program use is the limitation that the maximum number of nodes on a vertical grid line must not exceed 400. The following equations may be used to compute this number:

$$\text{BC1} \quad NC = (NP+1) + N1(L-1) + 2L \qquad [52]$$

$$\text{BC2} \quad NC = (NP+1) + N1(L-1) + L \qquad [53]$$

LOGICAL ERROR MESSAGES

The following error messages may be generated during execution. The boundary condition to which a particular error message applies is indicated by the BC column. If the same message applies to both boundary conditions, both numbers are shown.

No.	BC	Message
1	1	Computation of the stream function by subroutine SF0113 was attempted for a point outside the aquifer boundaries.
1	2	Computation of the stream function by subroutine SF0101 was attempted for a point outside the aquifer boundaries.
2	1	Computation of the stream function by subroutine SF0113 was attempted for the origin.
2	2	Computation of the stream function by subroutine SF0101 was attempted for the origin.
3	1	The series for the stream function did not converge according to the tests applied in subroutine SF0113. The maximum limit of 30 terms was reached.
3	2	The series for the stream function did not converge according to the tests applied in subroutine SF0101. The maximum limit of 999 terms was reached.
4	1,2	The number of nodes computed by subroutine SF0111 exceeds the dimensioned storage of 3,000.
5	1	The series for the constant lower case Q did not converge according to the tests applied in subroutine SF0114. The maximum limit of 30 terms was reached.
5	2	The series for the constant C did not converge according to the tests applied in subroutine SF0102. The maximum limit of 999 terms was reached.

No.	BC	Message
6	1	The series for the potential function did not converge according to the tests applied in subroutine SF0115. The maximum limit of 30 terms was reached.
6	2	The series for the potential function did not converge according to the tests applied in subroutine SF0103. The maximum limit of 999 terms was reached.
7	1,2	The number of points in a vertical column exceeds the dimensioned storage of 400.
8	1,2	The number of interpolated points exceeds the dimensioned storage of 3,000.
9	2	The number of points locating the streamlines exceeds the dimensioned storage of 3,000 after adding points at the water table.
10	1,2	The number of points defining a streamline exceeds the dimensioned storage of 3,000.
11	1	The series for the potential function did not converge according to the tests applied in subroutine SF0115. The maximum limit of 30 terms was reached. The subroutine to compute the potential function was called by SF0120.
11	2	The series for the potential function did not converge according to the tests applied in subroutine SF0103. The maximum limit of 999 terms was reached. The subroutine to compute the potential function was called by SF0120.
12	1,2	The number of points defining a streamline exceeds the dimensioned storage of 3,000 after subroutine SF0120.
13	2	The series for the potential function did not converge according to the tests applied in subroutine SF0103. The maximum limit of 999 terms was reached. Subroutine SF0103 was called by SF0122.
14	2	The ratio of the seepage rate to the permeability is equal to or greater than 1.00. There is no steady-state solution under these conditions. The case of uniform seepage must eventually yield the ponded water case.

No.	BC	Message
15	1,2	The number of required streamlines exceeds the dimensioned storage of 20. This number is being reduced to 20 by the program.

Messages 1, 2, and 15 are not fatal. The remaining messages are considered fatal and execution is terminated. If any of these error messages are encountered, the following tabulation suggests means to correct the deficiencies.

No.	Course of Action
1,2	These are nonfatal and are primarily debugging messages. Unless program changes are made, the user should never encounter them.
3,5,6,11,13	These fatal errors all involve failure of the various infinite series to converge. Details of the tests are contained in the program description. Two alternatives exist:

a. Increase the maximum number of terms in the given subroutine. It is set at the start of the subroutine by the arithmetic statement MMAX = 30 or MMAX = 999. Run times will increase.

b. Increase the test value for the ratio test in the given subroutine. It is set at the start of the subroutine by the arithmetic statement RATIØ = .000001. Both run times and solution accuracy will decrease.

The appropriate subroutines are included in the messages and are summarized as:

BC No.	Stream function	Solution constant	Potential function	No. of terms
1	SF0113	SF0114	SF0115	30
2	SF0101	SF0102	SF0103	999

Messages 3, 5, 6 are generated in computing values for nodes or interpolated points. Subroutine SF0120 in message 11 modifies points within the drain and adds one on the perimeter. Subroutine SF0122 in message 13 computes water table locations for BC2.

No.	Course of Action
4,7	These fatal errors involve the aquifer geometry and grid information. A redefinition of the grid using a coarser net is required. The equations in the main part of this manual can be used as guides. (See Equations for Number of Nodes.)
8,9,10,12	These fatal errors involve both the grid data and the number of streamlines. Either the grid should be made coarser or the number of streamlines reduced. Message 8 is generated during interpolation for all streamlines before adjustments at the drain or water table are made. Messages 9, 10, and 12 apply to a single streamline. Message 8 will normally be encountered before any of the others unless only 1 stream tube is used. Message 9 is generated for BC2 when points are added to the water table. Message 12 results when points are deleted and added at the drain.
14	This fatal error involves use of the wrong boundary condition based on the ultimate steady state. For normal drainage applications, this situation indicates severe waterlogging problems.
15	If more than 20 streamlines are desired, program dimensions for VOL(I), XST(I), and TRAVEL(I) must be increased. In addition, the error message generator in subroutine SF0112 must be changed.

SECTION XV

USER'S MANUAL

SATURATED CHEMISTRY PROGRAM

INTRODUCTION

The Saturated Chemistry Program was originally designed as part of the irrigation return flow quality model. Dutt and Shaffer(4) have presented the basic theory and concepts used. The program has been expanded to allow its use in return flow studies not utilizing the Unsaturated Flow and Chemistry Programs. Also, provision has been included for salt movement across the barrier (lower boundary), and user inputed values for ion exchange coefficients and CO_2 partial pressures.

The two-dimensional saturated system drained by parallel rows of circular drains is divided into a number of stream tubes. Discharge through each tube is identical although the soil mass is not. Individual tubes may also be subdivided into a number of elements, each having the same soil mass. As shown in Figure 25, these elements are in series with respect to the path of flow.

The system is defined by specifying the number of tubes and for each tube the total pore or water volume, average volumetric moisture content, stream tube width at the water table, and the number of subdivisions. Each tube can be initially treated as chemically homogeneous or each element can have a unique soils analysis. Once the system is operating, an initially homogeneous system will soon become heterogeneous due to different soil volumes in each tube, chemical reactions, and piston displacement effects of the deep percolation water. When a restart deck is punched at the end of a run, current soils data for every element in every tube reflect the heterogeneous condition.

Inputs to the saturated system include the amounts and quality of deep percolation water. This may be taped output from the unsaturated chemistry portion of the return flow model or may be input by cards. When cards are used, inputs may represent output from the unsaturated zone (either observed, predicted, or guessed data) or surface inputs. Surface inputs, in turn, would logically be used when the unsaturated zone is nonexistent (for example, the ponded water case), when the zone is bypassed because changes within it are minor in comparison to those in the saturated system, or when the program is being used to simulate the unsaturated zone. In this case, input data could be the estimated deep percolation and the corresponding quality of the applied

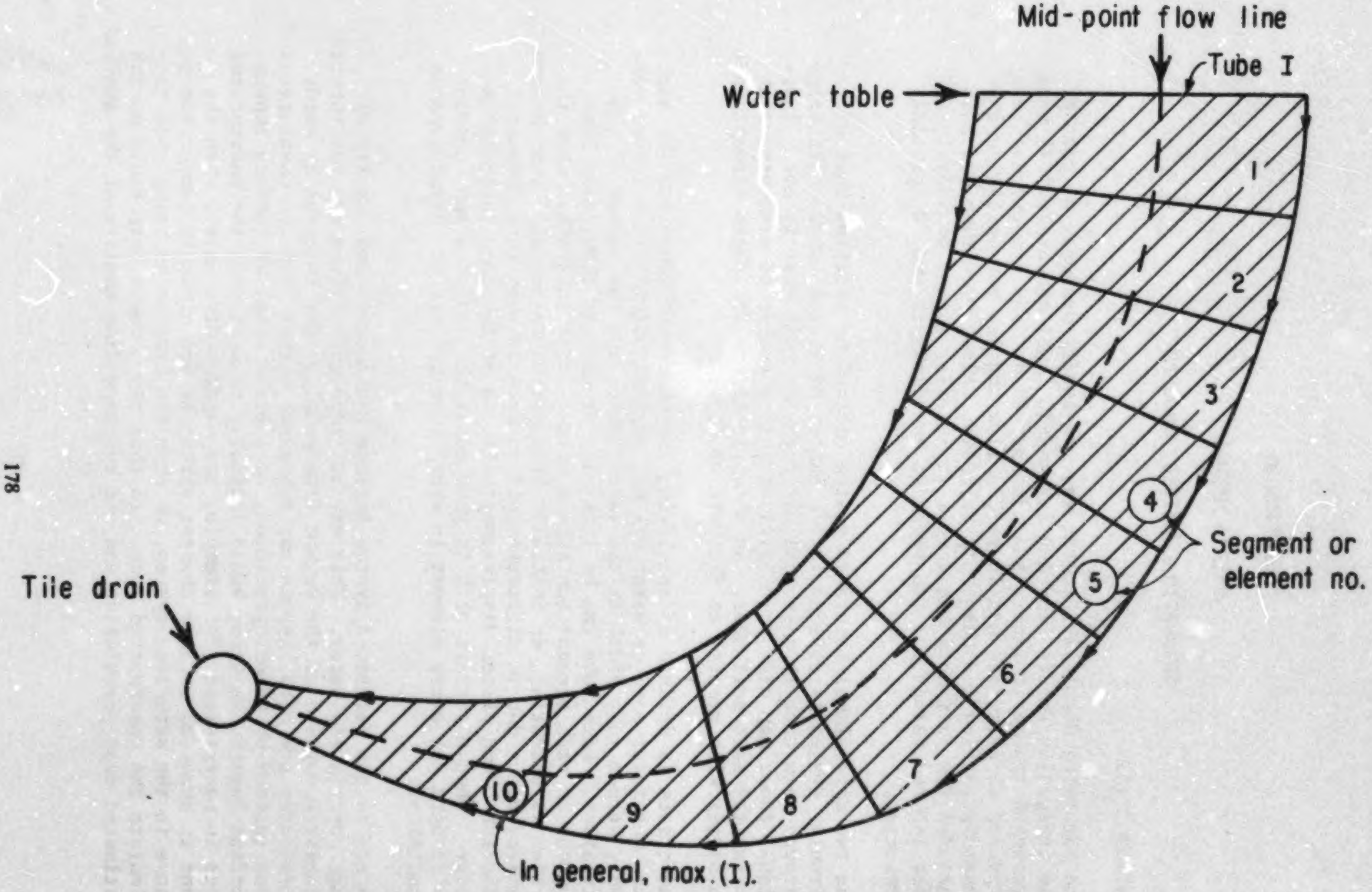

Mid-point flow line
Tube I
Water table
1
2
3
4
5
6
7
8
9
10
Segment or element no.
Tile drain
In general, max.(I).

FIGURE 25. SEGMENTED FLOW TUBE IN SATURATED REGION. EXAMPLE OF 10 SUBDIVISIONS. (MAX(I)=10)

water or water of surface quality can be entered along with the onfarm irrigation efficiency. In the later case, the program removes the consumptive use from the input water and concentrates it accordingly.

Output from the program includes printed results showing the quality of water discharging from each tube, punched restart chemistry decks, and taped quality output. The taped output is intended for input to the drain effluent prediction portion (program DE0200) of the water quality model.

UNIT NUMBERS

Card input is accomplished by READ statements without a unit number and listed output by means of PRINT statements. The common input (CIT) and output (COT) devices are understood to be used. Punched output (restart deck) is accomplished by PUNCH commands. In addition, the program references additional units:

Unit designation	Unit description or purpose
15	The unit on which the file containing deep percolation quantities and qualities is mounted. This file is written by the unsaturated chemistry portion of the water quality model. When these data are input by cards, they are transferred to unit 15 and the program functions as if a saved tape existed. (See Tape Input.)
16	The unit on which the file containing the quality of water discharging from each tube of the saturated system is mounted. This file is intended for input to the drain effluent prediction portion of the quality model. (See Tape Output.)
17	An internal scratch unit on which the last year's data are written. This allows repeated reading of these data as a single file.
18	Output data written to this file in format suitable for a read in a subsequent run as unit 15 (IWR must = 1).
20	This file contains 7 coded output giving the total number of slugs generated for each stream tube during the run. Information is used as partial input to the drain effluent prediction submodel.

DATA DECK STRUCTURE

There are six groups of input cards from which the data deck for a given run is composed, as shown in Figure 26. The format for each group, except group 6 (restart deck), is illustrated in Figure 26. Variables are defined below. Note that the card numbers refer to card types and not the actual number of a given type.

CARD GROUP 1 - Title Card

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	TITLE	An 80-character alphanumeric title used to identify the printed output.

CARD GROUP 2 - Control Card

Column No.	Var type	Var name	Variable description
Card 1 of 2			
1- 5	I	ICARD	Flag to indicate the input medium for the deep percolation inputs. If ICARD = 1, then read input from cards (group 5). If ICARD $\neq$ 1, then read input from magnetic tape (unit 15).
6-10	I	INFIL15	The initial file number to be read on unit 15. (See Tape Input.)
11-15	I	LSFIL15	The last file number to be read on unit 15. When deep percolation data are read from cards (ICARD = 1), LSFIL15 is the number of years of data. (See Tape Input.)
16-20	I	NREPT	The number of times the last file on unit 15 (LSFIL15) is to be repeated as input. This option is available for both tape and card input. (See Tape Input.)
21-25	I	INFIL16	The number of the initial file to be written on unit 16. (See Tape Output.)

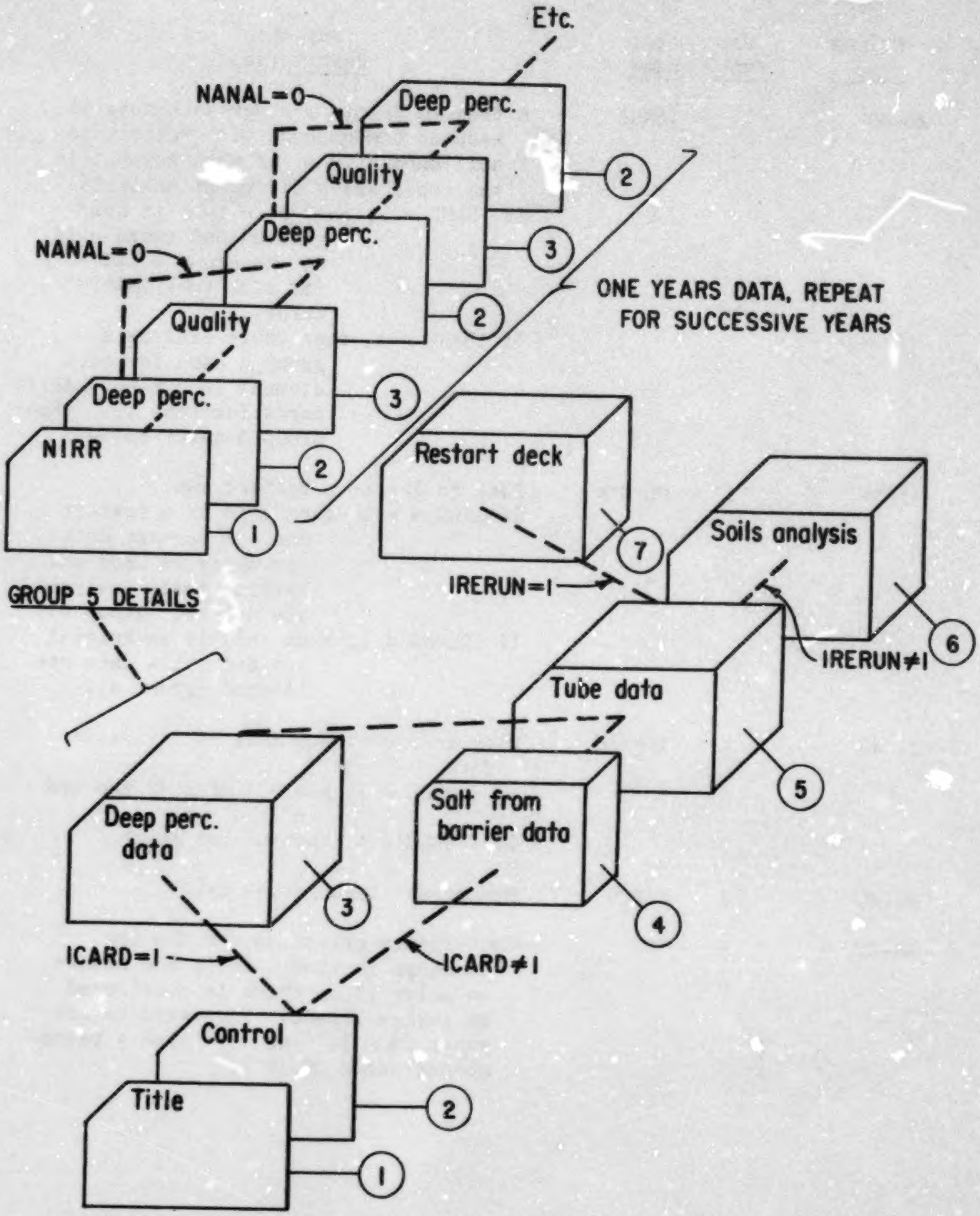
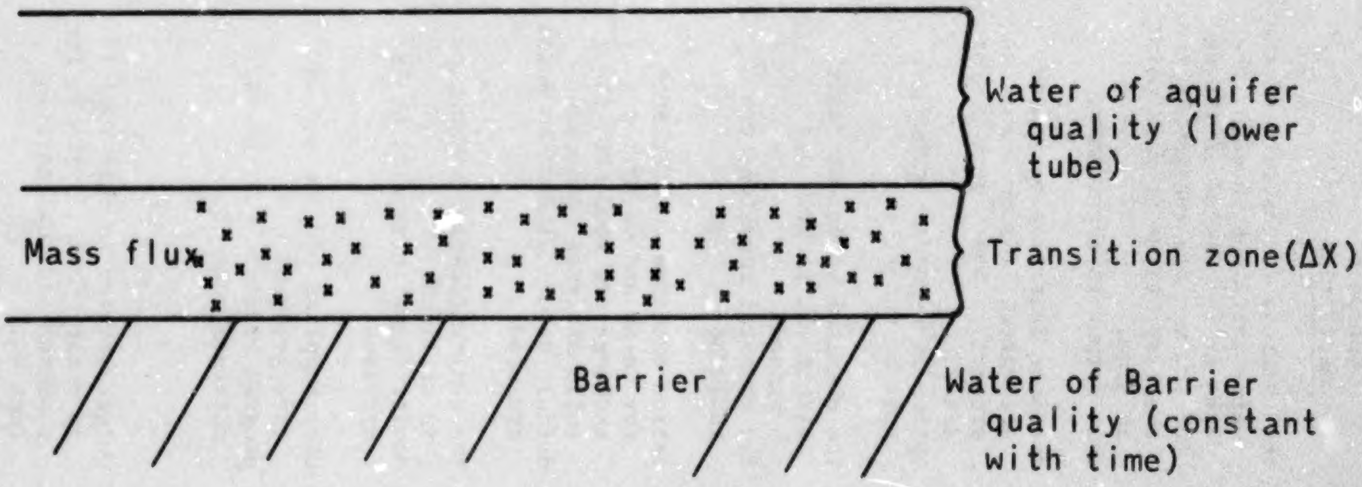

Etc.
NANAL=0
Deep perc.
Quality
Deep perc.
NANAL=0
Quality
Deep perc.
NIRR
②
③
②
③
②
①
ONE YEARS DATA, REPEAT FOR SUCCESSIVE YEARS
Restart deck
⑦
Soils analysis
⑥
IRERUN=1
IRERUN≠1
GROUP 5 DETAILS
Tube data
⑤
Deep perc. data
③
Salt from barrier data
④
ICARD=1
ICARD≠1
Control
Title
②
①

FIGURE 26. DATA DECK STRUCTURE SATURATED CHEMISTRY SUBMODEL

Column No.	Var type	Var name	Variable description
26-30	I	ISAME	A flag to denote whether each tube is assumed homogeneous with respect to soil chemistry or if each segment in the tubes has a different analysis. If ISAME = 1, then each tube is homogeneous and there will be one group 4 card for each tube (MAXTU cards). If ISAME ≠ 1, then there will be a group 4 card for each element in a tube (MAX(I) cards for tube I). (See group 3 cards below.)
31-35	I	IRERUN	Flag to denote a restart run. If IRERUN = 1, then this is a restart run. A restart deck (group 6) is used and initial soils analyses are deleted (group 4). If IRERUN ≠ 1, then this is an initial run and soils data are inputed (group 4).
36-40	I	IPUNCH	Flag to signal punching of a restart deck. If IPUNCH = 1, punch a deck at the end of the run. If IPUNCH ≠ 1, then do not punch.
41-45	I	MAXTU	Number of stream tubes used.
46-50	R	CH1	Convergence criterion for the ion exchange routine. It is the number of moles/liter which is considered as insignificant. Suggested values range from 10^{-2} to 10^{-6} with a recommended value of 10^{-4}. .

Column No.	Var type	Var name	Variable description
51-55	I	IDUMP	If = 1, the chemical composition of the water contained in each tube element is printed at the end of the run and represents the chemical status at this point in time. If = 0, this output is suppressed.
56-60	I	IINJE	If = 1, the salt injection option is activated. (Group 3 must be present.) See Figure 27 for details. If = 0, option is bypassed (group 3 must be absent).
61-65	I	SBYPAS	If = 1, the chemical reactions (salt) within the program are bypassed. If = 0, the chemical reactions are included.
66-70	I	IREK	If = 1, cation exchange coefficients for Ca-Na and Ca-Mg ion exchange are read from the soils analyses data cards. If = 0, default values within the model are used.
71-75	I	IDN	If = 1, the denitrification subroutine is utilized. If = 0, denitrification subroutine is bypassed.
76-80	I	IPC02	If = 1, user supplied pCO_2 values used (see group 6). If = 0, program relate: pCO_2 to soil moisture content.
Card 2 of 2			
1- 5	I	IWR	If = 1, output written to file Tape 18 in binary format suitable for a subsequent read as file Tape 15. If = 0, no write to file Tape 18.


Water of aquifer quality (lower tube)
Mass flux
Transition zone(ΔX)
Barrier
Water of Barrier quality (constant with time)

$\text{Mass Flux}_i = D\frac{\partial Ci}{\partial X}$ Basic equation

$\text{Mass Flux}_i = D\frac{\Delta Ci}{\Delta X}$ Approximate equation
(steady state)
(for any time step)

Where: Ci is the concentration of constituent i.

D is a mean diffusion coefficient.

FIGURE 27. SALT INJECTION FROM THE BARRIER

CARD GROUP 3 - Deep Percolation Data

This group is only used when ICARD = 1. It includes the three types of cards described below. Cards must be placed in chronological order with each year's data preceded by a type 1 card. This card is followed by the appropriate combination of card types 2 and 3 as indicated in Figure 26. (See NANAL below.) Checks are not made on the chronological order and it is possible to include more than one application on a single day by using separate type 2 cards. The total number of years of data is LSFIL15. (See Tape Input.)

Column No.	Var type	Var name	Variable description
Card 1 of 3			
1- 5	I	NIRR	Number of water applications or deep percolation inputs for the current year.
Card 2 of 3			Deep percolation volumes.
1- 5 6-10 11-15	I I I	IM0N, IDAY, IYEAR	The month, date, and year on which the deep percolation occurred. For example, July 17, 1973, would be IM0N = 7, IDAY = 17, IYEAR = 1973. The month and day are converted to the Julian day, which along with the year, is written on unit 15 for information purposes.
16-25	R	APP	Amount of deep percolation for this application (inches^3/inch^2 or inches). A + value is an input to the saturated system, while a - value denotes flow from the saturated to unsaturated system.
26-30	I	NANAL	Flag used to denote the need for a new water quality analysis. If NANAL = 0, the previously read analysis is to be used with this application. If NANAL $\neq$ 0, a new analysis is to be read and a type 3 card will immediately follow this type 2 card.

Column No.	Var type	Var name	Variable description
31-46	A	SOURCE	A 16-character alphanumeric name which can be used to identify the source of the deep percolation water. For example, PROJECT WATER or PRECIPITATION or SNOWMELT. It is printed on output for information purposes only.
47-56	R	E	Onfarm irrigation efficiency (percent basis).
Card 3 of 3			Quality analysis of deep percolation water.
1- 5	R	ANH4	Ammonium (NH_4+) concentration (meq/1).
6-10	R	ANO3	Nitrate (NO_3^-) Concentration (meq/1).
11-15	R	CA	Calcium (Ca^{++}) concentration (meq/1).
16-20	R	AMG	Magnesium (Mg^{++}) concentration (meq/1).
21-25	R	ANA	Sodium (Na^+) concentration (meq/1).
26-30	R	HCO3	Bicarbonate (HCO_3^-) concentration (meq/1).
31-35	R	CO3	Carbonate ($CO_3^=$) concentration (meq/1).
36-40	R	CL	Chloride (Cl^-) concentration (meq/1).
41-45	R	SO4	Sulfate ($SO_4^=$) concentration (meq/1).

CARD GROUP 4 - Data for Salt Movement (Injection) From Barrier

Column No.	Var type	Var name	Variable description
Card 1 of 2			
1-10	R	DIFK	Diffusion coefficient (cm^2/day) values range from about 1 to 20.
11-15	R	DIFDIS	Diffusion distance (cm).

Column No.	Var type	Var name	Variable description
16-20	I	MIN	First element of outside tube contacting barrier (as measured from surface of water table).
21-25	I	M0UT	Last element of outside tube contacting barrier.
26-30	R	SHCA	Concentration of Ca^{++} in barrier water (mg/1).
31-35	R	SHMG	Concentration of Mg^{++} in barrier water (mg/1).
36-40	R	SHNA	Concentration of Na^{+} in barrier water (mg/1).
41-45	R	SHC03	Concentration of $CO_3^{=}$ in barrier water (mg/1).
46-50	R	SHHC03	Concentration of HCO_3^{-} in barrier water (mg/1).
51-55	R	SHCL	Concentration of Cl^{-} in barrier water (mg/1).
56-60	R	SHS04	Concentration of $SO_4^{=}$ in barrier water (mg/1).
61-65	R	SHN03	Concentration of NO_3^{-} in barrier water (mg/1).
66-70	R	TRTME	Travel time to displace one slug in tube contacting barrier (days).
Card 2 of 2			
1-10	R	CLGT(L)	Length of contact of element L with barrier (cm).
11-20	R	CLGT(L+1)	Length of contact of element L with barrier (cm).

Column No.	Var type	Var name	Variable description
CARD GROUP 5 - Stream Tube Data			
Card 1 of MAXTU			
1-10	R	TUVEN(I)	Pore volume of tube (feet^3/foot of drain). Where I = 1 corresponds to the tube closest the drain and I = MAXTU to the tube farthest from the drain.
11-20	R	TUWEN(I)	Width of tube at the water table (feet).
21-30	R	THETA(I)	Volumetric moisture content of the tube at saturation. It is the ratio of the volume of water to the volume of soil (dimensionless).
31-40	I	MAX(I)	Number of elements or segments that the tube is to be divided into. (Program limits this value to 25 or less.)

Note: One card is needed for each tube.

CARD GROUP 6 - Soils Analysis Data

This group is only included for an initial run (IRERUN $\neq$ 1). There will be one card per tube if each tube is homogeneous (ISAME = 1) or one card per element in all tubes (MAX(I) card for tube I) if each tube is nonhomogeneous (ISAME $\neq$ 1). Cards should be in order, starting with tube 1 nearest the drain and ending with tube MAXTU farthest from the drain. Where there is one card per element, cards for a given tube should start with element 1 nearest the water table and end at element MAX(I) nearest the drain. (See Figure 25.) Note that element boundaries are not necessarily horizontal. This means that care must be taken when assigning soil chemistry data to each element. Most of the chemistry data comes from a soil extract analysis.

Card 1 of 2			(J denotes the element number.)
1-5	R	CA(J)	Calcium (Ca^{++}) concentration (meq/1).*

---

* Meq/1 denotes milliequivalents per liter.

Column No.	Var type	Var name	Variable description
6-10	R	AMG(J)	Magnesium (Mg^{++}) concentration (meq/1).
11-15	R	ANA(J)	Sodium (Na^{++}) concentration (meq/1).
16-20	R	ANH4(J)	Ammonium (NH_4^+) concentration (meq/1).
21-25	R	CL(J)	Chloride (Cl^-) concentration (meq/1).
26-30	R	S04(J)	Sulfate ($SO_4^=$) concentration (meq/1).
31-35	R	HC03(J)	Bicarbonate (HCO_3^-) concentration (meq/1).
36-40	R	C03(J)	Carbonate ($CO_3^=$) concentration (meq/1).
41-45	R	AN03(J)	Nitrate (NO_3^-) concentration (meq/1).
46-50	R	EC(J)	Cation exchange capacity (meq/100 gm of soil).
51-55	R	CAL(J)	Indicator as to whether soil is calcareous (lime present). If Cal(J) = 1.0, soil is calcareous. If CAL(J) = 0.0, soil is noncalcareous.
56-60	R	XX5(J)	Gypsum ($CaSO_4 \cdot 2H_2O$) content (meq/100 gm of soil). Residual gypsum content at moisture percentage of extract.
61-65	R	XTRCT(J)	Ratio of water to soil at which the soil extract was made, expressed as a decimal (gm water/gm soil).
66-70	R	BD(J)	Bulk density of the soil (gm of soil/cm^3 of soil).
71-75	R	AKCS(J)	Ca-Na exchange coefficient (if the default values are not wanted).
76-80	R	AKCM(J)	Ca-Mg exchange coefficient (if the default values are not wanted).

Column No.	Var type	Var name	Variable description
Card 2 of 2			
1-10	R	PC02(J)	CO_2 partial pressure in atmospheres.

Restart Deck

These cards are punched at the end of a run if IPUNCH = 1. They are reread on a restart run (IRERUN = 1) in which case initial soils data (group 4) are deleted. The cards are punched by the statement:

```
PUNCH (IFMT) JYEAR, KC0UNT, (ANH4(J), AN03(J), UREA(J), CA(J),
ANA(J), AMG(J), HC03(J), CL(J), C03(J), S04(J), EC(J), XX5(J),
CAL(J), E5(J), C5(J), SA5(J), CAS0(J), AGS0(J), BNH4(J),
CMH201(J), BD(J), IIK(J), AZE(J), J=1,N).
```

```
where IFMT = 2I5/(6E13.5/6E13.5/6E13.5/3E13.5, I5,E13.5)
followed by PUNCH(JFMT)    (H0LD(L),L=1,10)
where JFMT = 6E13.5/4E13.5.
```

The above cards are repeated for each tube. It is seen that there are 3+4xMAX(I) cards per tube for a total of MAXTU (3+4xMAX(I)) cards for all tubes. The variable definitions follow:

JYEAR - Current year number.

KC0UNT - Number of slugs out this tube so far.

J - Element or segment number within the tube. It goes from 1 to N where N is MAX(I).

ANH4(J) - Mass of ammonium nitrogen (NH_4-N) in element (ug)*.

AN03(J) - Mass of nitrate nitrogen (NO_3-N) in element (ug).

UREA(J) - Mass of urea nitrogen (Urea-N) in element (ug).

CA(J) - Mass of calcium (Ca^{++}) in element (ug).

ANA(J) - Mass of sodium (Na^{+}) in element (ug).

AMG(J) - Mass of magnesium (Mg^{++}) in element (ug).

---

* ug denotes 10^{-6} gms or micrograms.

HC03(J) - Mass of bicarbonate (HCO_3^-) in element (ug).

CL(J) - Mass of chloride (Cl^-) in element (ug).

C03(J) - Mass of carbonate ($CO_3^=$) in element (ug).

S04(J) - Mass of sulfate ($SO_4^=$) in element (ug).

EC(J) - Exchange capacity of element (eq/gm).

XX5(J) - Gypsum ($CaSO_4 \cdot 2H_2O$) concentration in element (moles/gm).

CAL(J) - Lime indicator for element as used on input for initial soils analysis.
If CAL(J) = 1.0, lime is present.
If CAL(J) = 0.0, lime is not present.

E5(J) - Exchangeable calcium (Ca^{++}) in element (moles/gm).

C5(J) - Exchangeable magnesium (Mg^{++}) in element (moles/gm).

SA5(J) - Exchangeable sodium (Na^+) in element (moles/gm).

CAS0(J) - Undissociated gypsum ($CaSO_4$) in element (moles/l).

AGS0(J) - Undissociated magnesium sulfate ($MgSO_4$) in element (moles/l).

BNH4(J) - Exchangeable ammonium (NH_4^+) in element (moles/gm).

CMH201(J) - Water content in element (cm^3).

BD(J) - Soil bulk density of element (gm/cm^3).

IIK(J) - Lime indicator for element as used internally.
If IIK(J) = 1, lime is present.

AZE(J) - Value proportional to intercept of the equation relating pCO_2 and soil moisture content.(5) A constant for each soil computed from the extract analysis.

H0LD(L) - Accumulated masses of various inputs to the saturated system that were left over after the last slug output was computed. For future runs, these partial sums are used to initialize the mass counters until a volume of water sufficient to displace the water in one element has been accumulated.

HOLD(1) - Volume of water (cm^3/cm of drain).

HOLD(2) - Mass of calcium (Ca^{++}) (ug/cm of drain).

HOLD(3) - Mass of magnesium (Mg^{++}) (ug/cm of drain).

HOLD(4) - Mass of sodium (Na^+) (ug/cm of drain).

HOLD(5) - Mass of ammonium nitrogen (NH_4-N) (ug/cm of drain).

HOLD(6) - Mass of chloride (Cl^-) (ug/cm of drain).

HOLD(7) - Mass of sulfate ($SO_4^=$) (ug/cm of drain).

HOLD(8) - Mass of bicarbonate (HCO_3^-) (ug/cm of drain).

HOLD(9) - Mass of carbonate ($CO_3^=$) (ug/cm of drain).

HOLD(10) Mass of nitrate-nitrogen (NO_3-N) (ug/cm of drain).

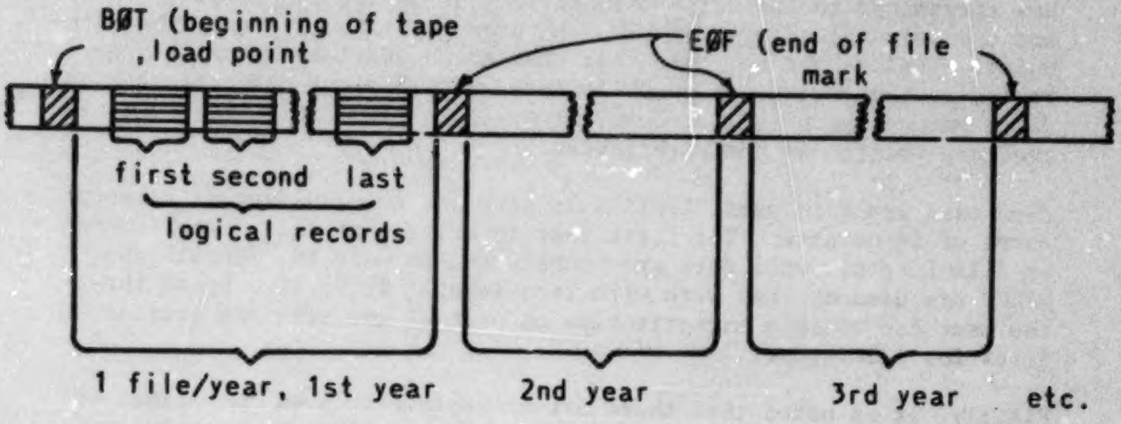
TAPE INPUT

Magnetic tape output from the unsaturated chemistry program (unit 2) can be used to input deep percolation data to the saturated chemistry program (unit 15). This tape contains the volume of water leached from the unsaturated zone and the corresponding mass of salts leached by constituents. Values are expressed on a per-unit area basis. The tape is written without format (binary) and is structured as shown in Figure 28.

Each file represents a year of data. In executing the saturated chemistry program, only full years are used. To allow for restarts, the user specifies the initial file (INFIL15) to be used as input for the first year computed by this run as well as the last file (LSFIL15). The program skips the first (INFIL15-1) files and positions for the initial read of the first logical record in INFIL15. The program then reads and executes through subsequent files until LSFIL15 has been read.

This last file may be repeatedly reread for future years' input by using the NREPT option. If NREPT $\geq$ 1, the program rereads and uses data in LSFIL15 a total of NREPT times. Logically, the user may wish to use this option if the data in LSFIL15 represent either an average year or the results when a "dynamic" equilibrium condition is attained.

When deep percolation data are input by cards (ICARD = 1), the inputs are written on unit 15 using the same file structure as for magnetic


BØT (beginning of tape
,load point
EØF (end of file
mark
first
second
last
logical records
1 file/year, 1st year
2nd year
3rd year
etc.

Each logical record is written by the binary write statement:

```
  WRITE(2)  1 YEAR, I DAY, SUMØUT, DELN, (AMT(I), DEL(1) I=1,10)
```

where 1 YEAR is the year number

1 DAY is the Julian day

SUMØUT is the accumulative leachate volume (cm^3/cm^2)

DELN is the delta-leachate volume since previous record was written (cm^3/cm^2)

AMT(I) is the cumulative mass of constituent 1 leached since the start of the run per unit area (10 ^{6}gm/cm^2 or ug/gm^2)

DEL(I) is the mass of constituent I leached since the last logical record was written per unit area (10 ^{6}gm/cm^2 or ug/cm^2)

Constituents:

I	Item	I	Item
1	nitrate-nitrogen (NO_3-N)	6	magnesium (Mg^{++})
2	ammonia-nitrogen (NH_4-N)	7	bicarbonate (HCO_3^-)
3	urea-nitrogen (Urea-N)	8	chloride (Cl^-)
4	calcium (Ca^{++})	9	carbonate ($CO_3^=$)
5	sodium (Na)	10	sulfate ($SO_4^=$)

FIGURE 28. ORGANIZATION OF TAPE 2 OUTPUT FROM UNSATURATED CHEMISTRY SUBMODEL

tape. In this case, inputs do not include urea. Individual card values correspond to the delta amounts written on the tape. Since these are the only values used by the saturated chemistry program, the accumulative values are not computed. The month and date are first converted to the Julian day which is then written along with the year and delta amounts on unit 15. Cumulative values plus the delta amount for urea are written as dummy variables.

When card input is used, LSFIL15 is also the total number of files or years of input data. The first year is written as file 1, the second as file 2, etc. Once data are transferred to unit 15, INFIL15 and NREPT are used as they were with tape input. It is also noted that the user can equip a magnetic tape on unit 15 and save the created files for future use.

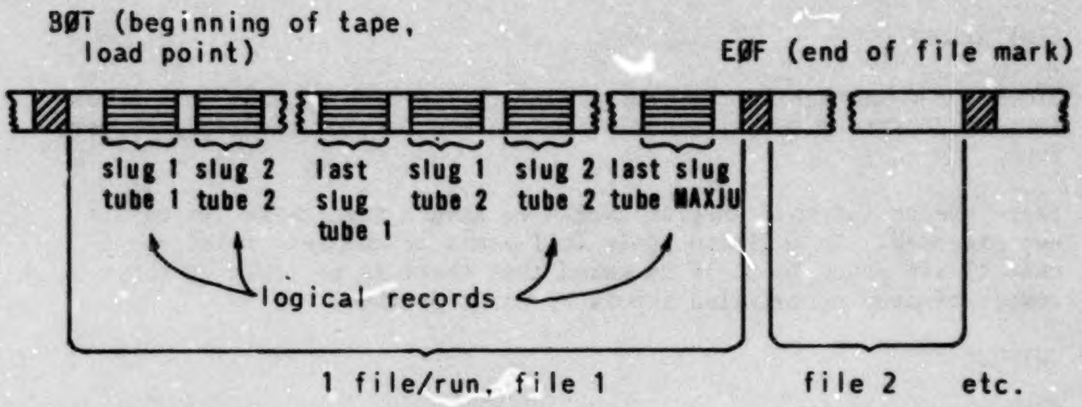
Finally, it is noted that there are no restrictions on the number of logical records in a file on unit 15. Although the unsaturated chemistry program outputs results on a daily basis, this is not required. The program reads all records in a file, using an end-of-file mark check to determine when a file has been exhausted. The number of records in each file may also vary.

TAPE OUTPUT

Magnetic tape output is written on unit 16 and is intended for input to the drain effluent portion of the water quality model. Individual runs of SATCHEM produce one file on unit 16. This file contains results starting with the first slug reaching the drain in tube 1 for the present run, followed by the second slug in tube 1, continuing until the last slug for tube 1 has been computed. Results for successive tubes up to MAXTU follow. When all tubes and slugs are finished, an end of file mark (EOF) is written. Thus, individual files can represent results for any number of years and the number of logical records per file may vary between files.

Figure 29 illustrates organization of the files and logical records on unit 16. Each logical record contains the tube number, slug number, and the concentration of the constituents in mgm/l. The slug numbers begin with slug 1 for the very first slug computed by the initial run and run consecutively, even for restart runs.

To allow restarts, the user must specify the initial file to be written on unit 16, INFIL16. The program then skips (INFIL16-1) files and positions the tape for the first write on INFIL16. For the initial run, INFIL16 should be left blank or set to 1.


BØT (beginning of tape, load point)
EØF (end of file mark)
slug 1 tube 1
slug 2 tube 2
last slug tube 1
slug 1 tube 2
slug 2 tube 2
last slug tube MAXJU
logical records
1 file/run, file 1
file 2
etc.

Each logical record is written by the binary write statement:

```
WRITE (16) I TUBE, KCØUNT, PPMNØ3, PPMNH4, PPMCA, PPMNA, PPMMC,
PPMHCØ3, PPMCL, PPMCØ3, PPMSØ4
```

where	ITUBE	is the tube number
	KCØUNT	is the slug number
	PPMNØ3	is the concentration of nitrate-nitrogen (NO_3-N) in mgm/l
	PPMNH4	is the concentration of ammonia-nitrogen (NH_4-N) mgm/l
	PPMCA	is the concentration of calcium (Ca^{++}) in mgm/l
	PPMNA	is the concentration of sodium (Na^{+}) in mgm/l
	PPMMG	is the concentration of magnesium (Mg^{++}) in mgm/l
	PPMHCØ3	is the concentration of bicarbonate (HCO_3^-) in mgm/l
	PPMCL	is the concentration of chloride (Cl^-) in mgm/l
	PPMCØ3	is the concentration of carbonate ($CO_3^{=}$) in mgm/l
	PPMSØ4	is the concentration of sulfate ($SO_4^{=}$) in mgm/l

FIGURE 29 ORGANIZATION OF TAPE 16 OUTPUT FROM SATURATED CHEMISTRY SUBMODEL

LIMITATIONS

Dimensioned storage in the program limits the problem size to: a maximum of 10 stream tubes; a maximum of 25 elements or subdivisions per tube.

There are no internal program checks to assure that these limits are not exceeded. In addition, only full years or complete files on unit 15 are processed. It is noted that there is no limit on the number of deep percolation inputs by cards or tape.

OUTPUT

Program output consists of printed listings, punched cards, and computed results written on magnetic tape.

Printed data listed by the program on the common print file is standard output. It includes:

a. Deep percolation volumes and qualities if input is by cards (ICARD = 1)

b. Control card data

c. Salt input from barrier data (IINJE = 1)

d. Constituent concentrations for each tube element at end of run (IDUMP = 1)

e. Stream tube inputs

f. Initial soil analyses (if IRERUN ≠ 1)

g. Outflow concentrations by constituents for each slug of every tube

Punched card output is optional, being selected by IPUNCH = 1. It consists of the restart deck which may be reused without modification for reruns.

Taped output on unit 16 is standard. If a saved magnetic tape is not desired, a physical tape should not be equipped on this unit.

SIMULATION OF UNSATURATED ZONE

The Saturated Chemistry Submodel can be utilized to simulate both chemistry and waterflow in the unsaturated zone. In cases where this technique can be applied, the savings in data collection/preparation and computer time can be substantial.

Coarse-textured and many medium-textured soils lend themselves to simulation by this method. A comparison of results obtained using the Unsaturated Flow and Unsaturated Chemistry Submodels with those obtained using the Saturated Chemistry Submodel provides a means of testing the efficacy of this technique for a particular soil.

In applying the submodel to the unsaturated zone, a single stream tube can be used to represent a one-dimensional flow path from the soil surface to the water table. The tube may be subdivided into some fixed number of elements or segments with equal volumes and spacing, or a single homogeneous segment can be selected.

Consumptive use of water within the root zone is assumed to occur in the upper most segment and water movement is assumed to occur at some characteristic "leaching" moisture content. The soil water content at field capacity is often used for this purpose.

The use of multiple segments in the soil profile adds desirable numerical dispersion to the simulation. About 10 segments per profile have been found to add sufficient dispersion.

Output is written on tape 18 in a format suitable for a direct read by the Saturated Chemistry Submodel as tape 15. In the latter case, the submodel would be used to simulate the saturated zone.

The following discussion summarizes details necessary to run the Saturated Chemistry Submodel in the unsaturated mode.

a. Input data can be read from tape 15 or from cards. If tape 15 is used, the consumptive use must already have been removed from the applied water. The program can remove the consumptive use if cards are utilized.

b. It is possible to assign a different initial chemistry to each segment by setting ISAME $\neq$ 1.

c. Set MAXTU = 1, unless more than one soil profile is being simulated per run.

d. If IDUMP = 1, a "picture" of the unsaturated profile chemistry will be printed at the end of the run.

e. Set IWR = 1 so that output file tape 18 will be written.

f. TUVEN(1) must be set equal to the occupied pore volume of the flow tube taken vertically from the soil surface down to a fixed water table.

For convenience, assume a 1-ft^2 column of soil and compute the pore volume occupied by water at field capacity or some other "leaching" water content as follows:

$$\mathrm{TUVEN(1)} = \mathrm{DEPTH} * \mathrm{THETA(1)}_{fc}$$

Where: DEPTH is the vertical depth to the water table (ft), and $\mathrm{THETA(1)}_{fc}$ is the volumetric soil water content at the "leaching" water content level.

g. Set TUWEN(1) equal to 1 ft.

h. Set THETA(1) equal to the value discussed under f. above.

i. Set MAX(1) equal to the number of segments desired in the in the tube (e.g. - 10).

j. Data for the soil chemical and physical parameters should be inserted into the input data deck with values for parameters closest to the soil surface associated with the first element or segment, etc. Values for PCO_2 and other parameters should be inserted to reflect the unsaturated soil profile.

SECTION XVI

USER'S MANUAL

DRAIN EFFLUENT PREDICTION PROGRAM

INTRODUCTION

This program is designed to combine or mix the water qualities and flow discharges from individual stream tubes extending from the water table to subsurface or surface drains.

Outputs from the drainout, saturated flow, and saturated chemistry programs are used as direct inputs to compute the quality and quantity of the drain effluent. When the saturated chemistry portion is bypassed, inputs from the unsaturated chemistry program are used.

In essence, the drain effluent program performs the routing process, modifies steady-state results when monthly discharge data are used, performs certain computations to obtain salt loads (masses), and generates the required output. This output includes listings and punched cards.

PROGRAM APPLICATION

There are two computational methods included in the drain effluent program. The method used depends on the manner in which the quality input data are developed. Briefly, in one case the inputs represent the quality of leachate water and in the other the quality of the discharges from the individual flow tubes.

Output from either method includes printed results. An optional card output is also available when monthly drain discharges are used. Concentrations of each parameter and salt load results can be selected.

There are many similarities in the inputs required by either computational method. However, understanding the basic differences between the two types of quality inputs will be helpful in applying the drain effluent program. The two cases are discussed below.

QUALITY OF LEACHATE WATER IS INPUT

When this approach is used, chemical transformations in the saturated zone are not simulated and the saturated chemistry program is bypassed. The drain effluent program merely routes the leachate water and its salts down each stream tube to the drain.

Steady-state flow is assumed and piston displacement theory is applied to each tube. When the quality of the leachate water is changed at a given time, a "front" dividing this water from that previously entering the saturated system is assumed to form. The front is assumed to travel down each stream tube in accordance with the travel times computed by the saturated flow program. The relative arrival times of the front at the drain for each tube are then used to combine results from each tube yielding the drain effluent quality.

Leachate water quality inputs can be entered by card input or by an edited form of the taped output from the unsaturated chemistry program. Although card input is usually limited to testing and "debugging," they can be used to input observed field data for verification purposes.

Because the final results are based on a steady-state (average) discharge, outputs from the unsaturated chemistry program must be edited so that each change in quality corresponds to the proper volume of leachate water. Since the unsaturated chemistry program produces both variable leachate volumes and qualities on a daily basis, it is necessary to edit the data so that inputs are based on equal volumes of water. The corresponding average concentrations of each parameter are then computed. This is accomplished by a utility program called EDITC0 (see Suggested Improvements).

When cards are used, unequal time steps may be used, with inputs only being required each time the leachate water quality changes. However, the volume of water is assumed equal to that which would exist under steady-state drain discharge.

DATA FROM SATURATED CHEMISTRY PROGRAM IS INPUT

When the saturated chemistry program is used, each stream tube is subdivided into a number of equal volumed segments. Leachate water is accumulated until the volume corresponds to the pore volume of the segment. The mass of each parameter is also accumulated, resulting in a water having the average concentration during the given time period. This volume of water with its associated quality is referred to as a slug.

The saturated chemistry program then passes the slug down the tube through successive segments, simulating the various chemical transformations. The final result is the quality of water in each slug which discharges into the drain from a given tube. It is this discharging water quality that is placed on tape by the saturated chemistry program and used as input to the drain effluent program.

Because chemistry changes in the saturated system are not simulated when leachate water is input to the drain effluent program, the discharging water quality is eventually identical to that of the leachate water. This is true for every stream tube. However, when the saturated chemistry inputs are used, each tube will have different discharging water qualities, at least until a "dynamic" equilibrium condition is reached.

The relative timing of each slug arrival is based on an average drain discharge and the corresponding travel times. When this is done, results represent average qualities for equal increments of discharge. However, monthly drainage volumes determined by the drainout program can be used to modify the steady-state results. The variable discharge pattern is then used to compute the average monthly concentrations.

UNIT NUMBERS

Six logical unit numbers are referenced when the quality of leachate water is input: 5, 6, 7, 8, 16 and 29. When the saturated chemistry results are used as input there are 7+NST units referenced: 5, 6, 8, 9, 16, 29, 62, and MUNIT = 16+1 to 16+NST where NST is the number of stream tubes. Since the maximum number of stream tubes is 10, the maximum number of units is 17.

Unit numbers are:

Unit designation	Unit description or purpose
5	The common input tape or unit (CIT). It is the computer systems standard input device.
6	The common output tape or unit (CØT). It is the computer systems standard output device.
7	The unit on which the "formula" or equation giving the composition of the drain effluent is written (see Suggested Improvements). It is only used when the leachate water quality is input. This is normally a scratch unit and is written with unformatted (binary) writes. However, it may be equipped and saved. Subsequent runs must specify a saved tape by setting IØC(7) = 1, 2, or 3.
8	The unit on which all data necessary for plotting concentrations or for computing the salt load results is written. It is written in binary form and is usually

Unit designation	Unit description or purpose
	considered a scratch unit although it may be equipped and saved for future use. It is used when input is the leachate water quality or the drain effluent quality, although the structure and data are slightly different. For: input of leachate water quality (IØC(4) = 1 or 2), unit 8 is written when salt load results are requested (IØC(5) = 1 or 2) or when a saved tape is requested (IØC(6) = 1). When IØC(7) = 2 or 3, then a previously generated saved tape on unit 8 is indicated and must be included in the run. input of the drain effluent quality (IØC(4) = 3), unit 8 is written when monthly concentrations are to be computed (IØC(10) = 1) provided a request is specifically made to create a saved tape (IØC(6) = 1). It is used for subsequent runs by setting IØC(8) = 1.
9	The scratch unit on which the computed drain effluent quality (composite of all tubes) for all parameters is written each time a slug reaches the drain. It is only used when the saturated chemistry results are used as input (IØC(4) = 3).
16	The unit on which the tape containing the quality inputs is mounted. Either leachate water is input (IØC(4) = 2) or the saturated chemistry tape is used (IØC(4) = 3). Data on the magnetic tape mounted on unit 16 is not formated and is in binary form. The tape structure is shown in Figure 29 for the case where the quality of leachate water is input and in Figure 30 when the drain effluent quality is input.
MUNIT	The logical unit on which the water quality inputs from the saturated chemistry program (as read from unit 16 when IØC(4) = 3) are transferred. It is an internal scratch unit on which the data is written in binary form.

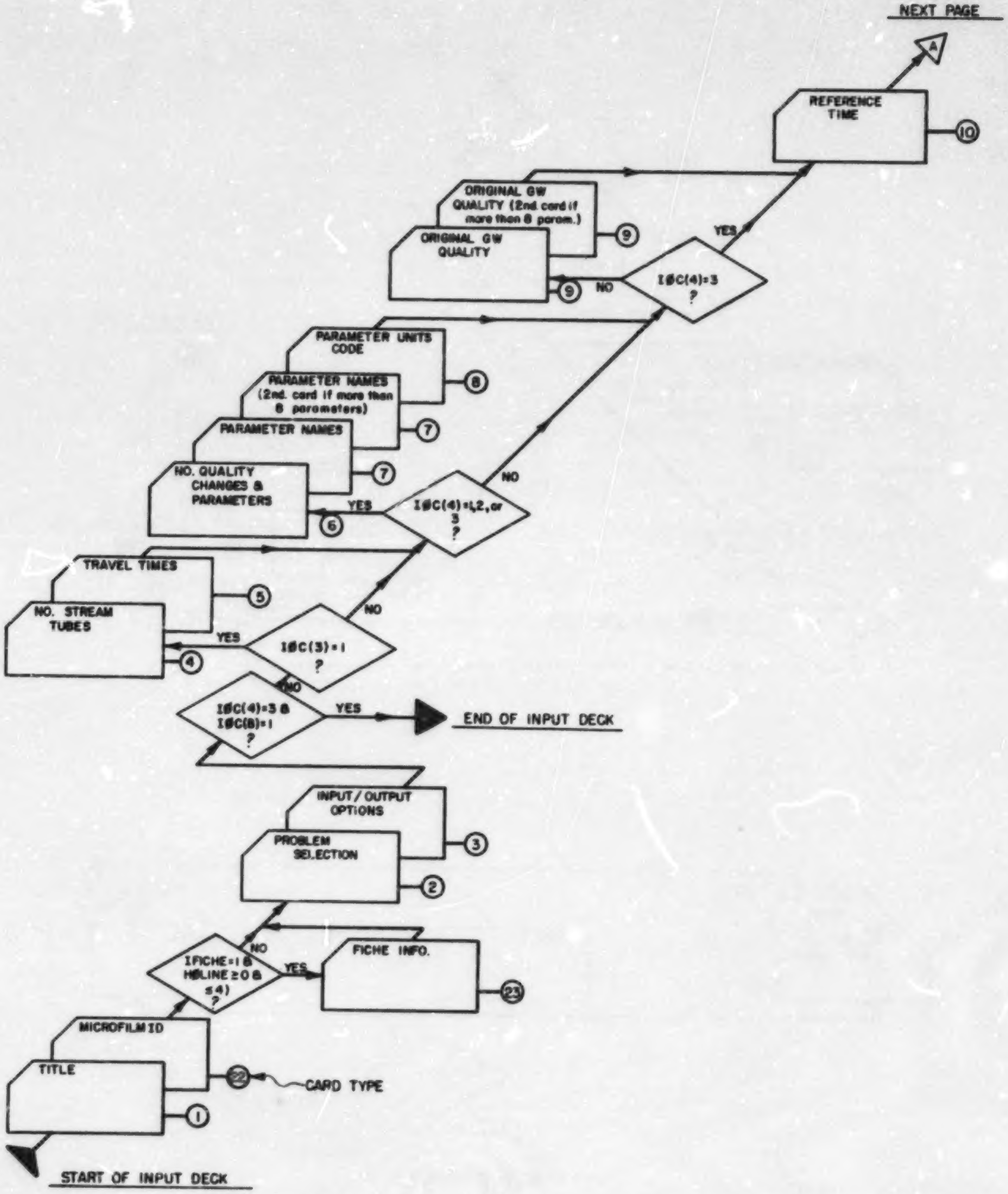

NEXT PAGE
A
REFERENCE TIME
10
ORIGINAL GW QUALITY (2nd. card if more than 8 param.)
9
ORIGINAL GW QUALITY
9
YES
NO
IØC(4)=3 ?
PARAMETER UNITS CODE
8
PARAMETER NAMES (2nd. card if more than 8 parameters)
7
PARAMETER NAMES
7
NO. QUALITY CHANGES & PARAMETERS
6
YES
NO
IØC(4)=1,2, or 3 ?
TRAVEL TIMES
5
NO. STREAM TUBES
4
YES
NO
IØC(3)=1 ?
NO
IØC(4)=3 & IØC(8)=1 ?
YES
END OF INPUT DECK
INPUT / OUTPUT OPTIONS
3
PROBLEM SELECTION
2
NO
IFICHE=1 & HØLINE ≥ 0 & ≤ 4) ?
YES
FICHE INFO.
23
MICROFILM ID
22
CARD TYPE
TITLE
1
START OF INPUT DECK

FIGURE 30. DATA DECK STRUCTURE-DRAIN EFFLUENT PREDICTION SUBMODEL

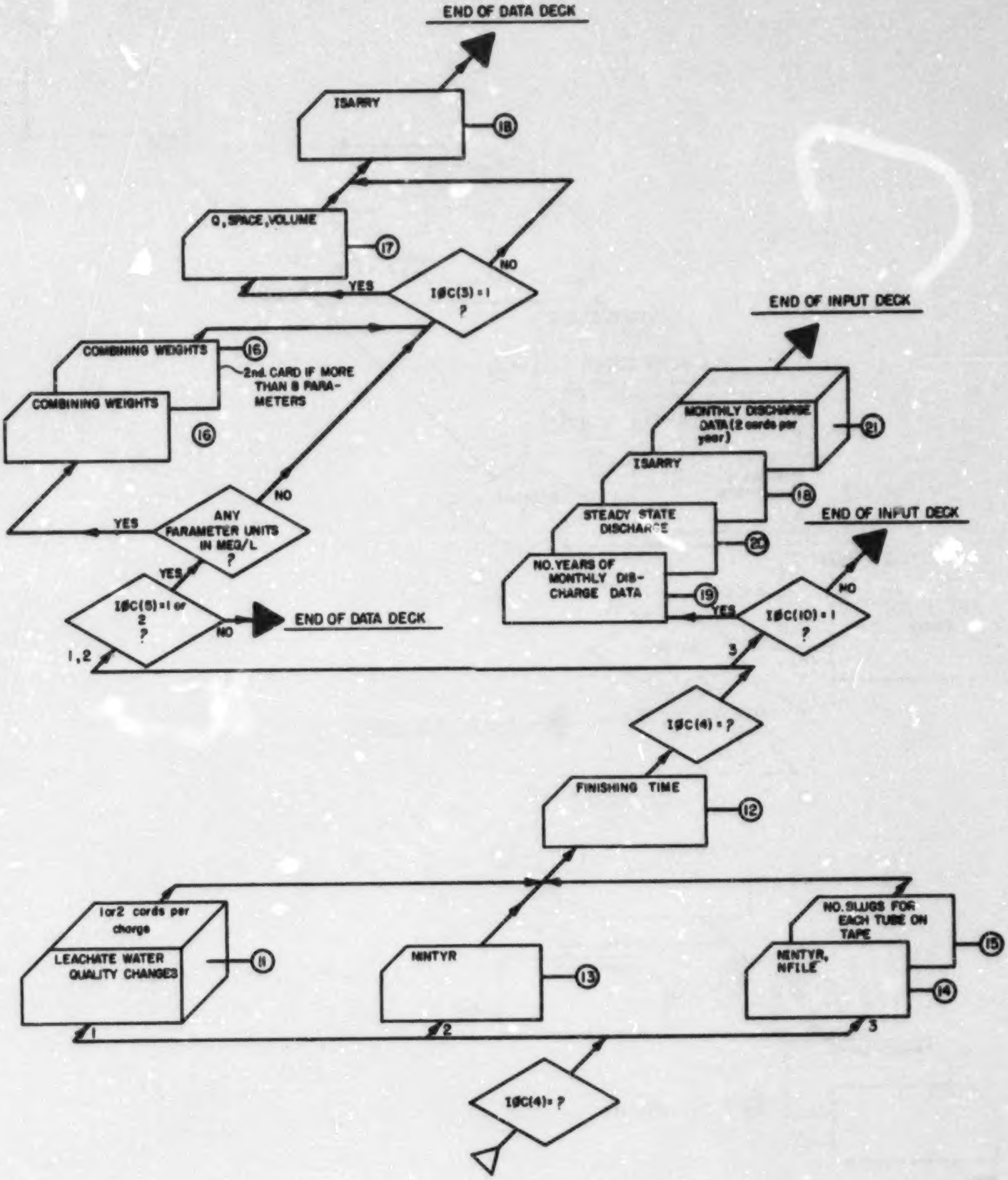

END OF DATA DECK
ISARRY
18
Q, SPACE, VOLUME
17
NO
YES
IOC(3) = 1 ?
END OF INPUT DECK
COMBINING WEIGHTS
16
2nd. CARD IF MORE THAN 8 PARAMETERS
COMBINING WEIGHTS
16
MONTHLY DISCHARGE DATA (2 cards per year)
21
ISARRY
18
NO
ANY PARAMETER UNITS IN MEG/L ?
YES
STEADY STATE DISCHARGE
END OF INPUT DECK
20
NO. YEARS OF MONTHLY DISCHARGE DATA
19
NO
YES
YES
IOC(5) = 1 or 2 ?
NO
END OF DATA DECK
IOC(10) = 1 ?
1, 2
3
IOC(4) = ?
FINISHING TIME
12
1 or 2 cards per charge
LEACHATE WATER QUALITY CHANGES
11
NINTYR
13
NO. SLUGS FOR EACH TUBE ON TAPE
15
NINTYR, NFILE
14
1
2
3
IOC(4) = ?

FIGURE 30. (CONTINUED)

Unit designation	Unit description or purpose
	The data for each stream tube are placed on different units with MUNIT starting one higher than 16, being incremented by one for each additional tube. Thus: MUNIT = 16 + 1 for stream tube 1 MUNIT = 16 + 2 for stream tube 2 . . . MUNIT = 16 + NST for stream tube NST Since NST has a maximum value of 10, MUNIT will range from 17 through 26.
29	The unit to which plotter commands are written when the plot subroutines are included in the model. This corresponds to the default unit number when the CRT unit is not specified by the user.
62	The card punch unit of the computer system.

DATA DECK STRUCTURE

There are 23 types of input cards in the input deck, as shown in Figure 30. The variables are defined below. It should be noted that not all card groups are included in a given run.

CARD GROUP 1 - Title Information

Column No.	Var type	Var name	Variable description
Card 1 of 1			
1-80	A	TITLE	An 80-character alphanumeric title used to identify all printed and plotted output. If this title is desired to be centered on output, it must be centered on the card.

Column No.	Var type	Var name	Variable description
CARD GROUP 2 - Problem Selection			
Card 1 of 1			
1	I	IPRØB(1)	A control array which calls the proper overlay for execution. Individual programs in the water quality model were originally designed for inclusion in an overlay system. Presently only the saturated flow and drain effluent portions are included. When IPRØB(I) is set to 1, the Ith ovorlay is called. The program will accept up to 40 entrys. Thus: IPRØB(1) = 1, call the saturated flow routine IORØB(2) = 1, call the drain effluent routine On output, values of IPRØB(I) are listed as IØC values under the heading PROBLEM CONTROL INFORMATION FOR MAIN PROGRAM.
2	I	IPRØB(2)	
.	.	.	
.	.	.	
.	.	.	
40	I	IPRØB(40)	
CARD GROUP 3 - Input/Output Options			
Card 1 of 1			
1	I	IØC(1)	An input/output option array used to specify the type of inputs, the required computations and the printed and plotted output. (See Input/Output Options for details.)
2	I	IØC(2)	
.			
.			
.			
40	I	IØC(40)	
CARD GROUP 4 - Number of Stream Tubes			
Card 1 of 1			
1-10	I	NST	The number of stream tubes to be used. When the saturated chemistry output is used, NST must correspond to the number used in the saturated chemistry program.

CARD GROUP 5 - Travel Times

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-8	R	TRAVEL(1)	Time of travel assuming piston displacement down tube I (years). I = 1 corresponds to the tube nearest the drain, I = 2 to the next closest tube, etc. These values are computed by the saturated flow program and are part of its output. Up to 10 travel times can be included.
9-16	R	TRAVEL(2)	
.	.	.	
.	.	.	
.	.	.	
73-80	R	TRAVEL(10)	

CARD GROUP 6 - Number of Quality Changes and Parameters

Card 1 of 1

1-5	I	NUQUCH	The number of changes in the quality of the leachate water when either cards are used to input quality (IØC(4) = 1) or when input is from the unsaturated chemistry program (IØC(4) = 2). When input is the saturated chemistry program results (IØC(4) = 3), NUQUCH is the maximum number of slugs leaving any tube. It will always correspond to tube 1. The value is obtained from the saturated chemistry programs printed output.
6-10	R	NUQUPA	The number of quality parameters being considered. It includes the number of anions plus the number of cations, but does not include the total load. NUQUPA must correspond to the number of parameters used in the unsaturated or saturated chemistry programs when their output is used. NUQUPA must be in the range 1 $\le$ NUQUPA $\le$ 15.

Column No.	Var type	Var name	Variable description

CARD GROUP 7 - Parameter Names

Card 1 of N

1-10	A	APANAM(1)	A 10-character alphanumeric name used to identify the quality parameter, where I = 1 to NUQUPA. (N = 1.) If NUQUPA exceeds 8, two cards are required (N = 2): the first giving APANAM(1) - APANAM(8) and the second giving APANAM(9) - APANAM(NUQUPA). These labels are used to identify all printed and plotted output, and should be in the same order as the quality inputs coming from cards (I0C(4) = 1) or from the chemistry programs (I0C(4) = 2 or 3).
.	.	.	
.	.	.	
.	.	.	
71-80	A	APANAM(8)	
(All fields may not be used)			

Card N of N

1-10	A	APANAM(9)	
.	.	.	
.	.	.	
.	.	.	
61-70	A	APANAM(15)	
(All fields may not be used)			

CARD GROUP 8 - Parameter Units Code

Card 1 of 1

1	I	IUNIT(1)	A numeric units code for parameter I where the order is identical to that for APANAM(I) and the quality inputs. If IUNIT(I) = 1, the units are in milligrams/liter. (On output they are labeled MG/L) IUNIT(I) = 2, the units are in milliequivalents/liter. (On output they are labeled MEQ/L.)
2	I	IUNIT(2)	
.	.	.	
.	.	.	
15	I	IUNIT(15)	
(All fields may not be used)			

Column No.	Var type	Var name	Variable description
CARD GROUP 9 - Original Ground Water Quality			
Card 1 of N			
11-18	R	QUAL(1)	The initial or original quality of the ground water at the start of the run for parameter I where the order is identical to that for APANAM(I) and the other quality inputs. Units for the initial quality must correspond to those specified by IUNIT(I). If NUAUPA $\leq$ 8, N = 1 If NUAUPA $\overline{>}$ 8, N = 2
19-26	R	QUAL(2)	
.	.	.	
.	.	.	
.	.	.	
67-74	R	QUAL(8)	
(All fields may not be used)			
Card N of N			
11-18	R	QUAL(9)	If there are more than 8 parameters, 2 cards must be used with the first giving QUALI(1) - QUALI(8) and the second QUALI(9) - QUALI(NUQUPA). It is noted that the original ground water quality is only used when the saturated chemistry results are not used. Since chemical transformations are not simulated and piston displacement is assumed, the leachate water is merely routed to the drains. The aquifer is assumed to be homogeneous with respect to water quality and the quality of the drain discharge will be identical to the initial quality until the first front reaches the drain.
19-26	R	QUAL(10)	
.	.	.	
.	.	.	
.	.	.	
59-66	R	QUAL(15)	
(All fields may not be used)			
CARD GROUP 10 - Reference Time			
Card 1 of 1			
1-10	R	TIMREF	The reference time to be used as the initial time at the start of the run (years). It must be consistent with times on the type 11 and type 12 cards. TIMREF could be 0.0, 1974, etc.

CARD GROUP 11

Leachate water quality changes Group N cards must be arranged in chronological order, starting with the first change and ending with the last change (NUQUCH).

Card 1 of N

Column No.	Var type	Var name	Variable description
1-10	R	TIQUCH(I)	The time of water quality change I (years). It must use the same time base as TIMREF. Thus, if TIMREF = 1974 and the first change is half-way through the first year, TIQUCH(1) = 1974.5 years.
11-18	R	PPM(I,1)	The quality of parameter J for the Ith change. Units correspond to those specified on the group 8 card. Parameters are arranged in the same order as APANAM(J) and the other inputs. It is noted that PPM(I,J) is the actual quality at this time, rather than an incremental or delta value. If there is no change for a given parameter at this time, the corresponding PPM(I,J) may be left blank. The program will then use the previous value. Thus, only parameters actually experiencing changes need be punched on cards.
19-26	R	PPM(I,2)	
.	.	.	
.	.	.	
.	.	.	
67-74	R	PPM(I,8)	
(All fields may not be used)			
Card N of N			If there are more than 8 parameters, two Group 11 cards are required. The first card will contain quality for parameters 1 through 8 while the second contains quality for parameters 9 through NUQUPA.

Column No.	Var type	Var name	Variable description
CARD GROUP 12 - Finishing Time			
Card 1 of 1			
1-10	R	TIMFIN	The time at which the run is terminated (years). It must use the same time base as TIMREF. For example, if a 16-year run is desired and TIMREF = 1974, TIMFIN = 1974 + 16. = 1990.
CARD GROUP 13 - Unsaturated Chemistry Tape Information			
Card 1 of 1			
1-5	I	NINTYR	The number of equal time intervals per year on the special unsaturated chemistry tape produced by the utility program EDIT0. (See Figure 30 for tape for mat.)
CARD GROUP 14 - Saturated Chemistry Tape Information			
Card 1 of 1			
1- 5	I	NINTYR	The number of elements or segments that each stream tube was divided into in running the saturated chemistry program. (For example, if 0.1 pore volumes were used, NINTYR would be 10.) It is noted that although the saturated chemistry program allows for a different number for each tube, the drain effluent program requires the same number.
6-10	I	NFILE	The number of files of data on the saturated chemistry output tape that are to be read [3, Tape Output]. Individual runs of program SATCHEM produce one file. The organization of each file is shown in Figure 29.

Column No.	Var type	Var name	Variable description

CARD GROUP 15 - Number of Slugs for Each Tube on Tape

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	I	NØSLUG(1)	The total number of slugs of water reaching the drain that are contained on the saturated chemistry input tape where I = 1 corresponds to the tube adjacent to the drain, I = 2 to the next closest, etc. The values of NØSLUG(I) are obtained from the printed output of the saturated chemistry program, or from tape unit written by saturated chemistry.
6-10	I	NØSLUG(2)	
.	.	.	
.	.	.	
.	.	.	
46-50	I	NØSLUG(10)	

(All fields may not be used)

CARD GROUP 16 - Combining Weights

Card 1 of N

Column No.	Var type	Var name	Variable description
1-10	R	CØMWT(1)	The combining weight of parameter I where the order is identical to that for APANAM(I) and the other quality inputs. The combining weights are equal to the atomic weight divided by the valence and are used to convert qualities in milliequivalents/liter to milligrams/liter. When quality inputs are by cards and the units specified by IUNIT(I) are in milliequalvalents/liter for one or more parameters, then the combining weight card is required. Only the combining weights for those parameters expressed in MEQ/L need be included with the others left blank.
11-20	R	CØMWT(2)	
.	.	.	
.	.	.	
.	.	.	
71-80	R	CØMWT(8)	

(All fields may not be used)

Card N of N

Column No.	Var type	Var name	Variable description
1-10	R	CØMWT(9)	When there are more than 8 parameters, two cards must be included. The first will contain combining weights for parameters 1-8 and the second for parameters 9 - NUQUPA.
11-20	R	CØMWT(10)	
.	.	.	
.	.	.	
.	.	.	
61-70	R	CØMWT(15)	

(All fields may not be used)

Column No.	Var type	Var name	Variable description

CARD GROUP 17 - Steady-state Drainage Data

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	Q	The steady-state drain discharge (cubic feet/year/foot of drain). It is the total discharge from the aquifer on both sides of the drain. The numerical value can be obtained from the saturated flow program's printed output.
11-20	R	SPACE	The horizontal drain spacing (feet).
21-30	R	VØLUME	The volume of water stored in the aquifer from the water table to the barrier between drains (cubic feet/foot of drain). When all salt load computations are requested (IØC(5) = 2), the VØLUME must be included. Otherwise the program will not use it.

CARD GROUP 18 - Total Load Array

Card 1 of 1

Column No.	Var type	Var name	Variable description
1	I	ISARRY(1)	A flag used to indicate which parameters are to be included in the TØTAL LØAD, where I is the parameter in the same order as APANAM(I) and the other quality inputs. If: ISARRY(I) = 1, then include this parameter in the TØTAL LØAD. ISARRY(I) ≠ 1, then exclude this parameter from the TØTAL LØAD.
2	I	ISARRY(2)	
.	.	.	
.	.	.	
.	.	.	
15	I	ISARRY(15)	
(All fields may not be used)			

CARD GROUP 19 - Number of Years of Monthly Discharge Data

Card 1 of 1

Column No.	Var type	Var name	Variable description
1- 5	I	NYEARS	The number of years of monthly discharge data that are to be read. These data are contained on the type 21 cards which are output from the drainout program.

CARD GROUP 20 - Steady-state Discharge

Card 1 of 1

Column No.	Var type	Var name	Variable description
1-10	R	Q	The average yearly drain discharge used to calculate arrival times in the saturated flow program (acre-feet/acre/year).

CARD GROUP 21 - Monthly Discharge Data

These cards are output from the drainout program, except for the title card which is eliminated.

Card 1 of M

Column No.	Var type	Var name	Variable description
1- 5	I	IYEAR	The year number of the data.
6- 7	I	ICRD	The card order within the year. ICRD = 1 contains data for the first 6 months and ICRD = 2 contains data for the second 6 months.
8-19	R	QMØN(1)	The monthly drain discharge for month I where I = 1 is January, I = 2 is February, etc. (acre-feet/acre/month).
20-31	R	QMØN(2)	
.	.	.	
.	.	.	
.	.	.	
	R		

CARD GROUP 22 - Microfilm Identification

The model version included in Volume V does not include plot subroutines. However, a blank card must be added here.

CARD GROUP 23 - Fiche Header Card Information

Fiche capability not included in this version of the model. No card(s) needed.

Input/Output Options

Individual input, computation, and output options are specified by setting the appropriate IØC(I) variable to the desired value on the group 3 card. For many options, the variables act as switches with a value of 1 turning the option on and any other value leaving it off.

Except for I0C(21) which controls card output individual printed output options are selected by the I0C(11) - I0C(25) variables. An individual option is selected by setting the I0C(I) value to 1. All of these options, except for I0C(21) can be selected by setting I0C(1) = 1. This eliminates the need of turning the individual options on.

Plotted* output options are selected by the I0C(26) - I0C(40) variables.

The two basic methods of inputing water quality changes are selected by the I0C(4) option. When I0C(4) = 1 or 2 the quality of leachate water is used (i.e. water leaving the unsaturated zone) and if I0C(4) = 3 the drain effluent quality is used (i.e., results computed by the saturated chemistry program). Some options are used for both cases while others apply to only one. Tables 16 and 17 summarize this information and include a list of options that are presently unused. Restrictions in the use of each option are also noted in the following list.

I	Value	Option
1	1	Select all print options, I0C(11) - I0C(25). (I0C(21) is not included since it is a punch option)
2	1	Select all plot options, I0C(26) - I0C(40).
3	1	Read all required saturated flow data from cards. This includes the number of stream tubes (card type 4), the travel times (card type 5) as well as the steady-state discharge, drain spacing and volume of water in storage (card type 17) when the leachate water quality is input (I0C(4) = 1 or 2) and salt load computations are requested (I0C(5) = 1 or 2).
3	≠1	The above data are expected to be in C0MM0N storage as a result of running the saturated flow program first.
4	-	This option controls the manner in which quality inputs are made to the program.
4	1	The quality of the leachate water is input via cards (card type 11).

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* Plot routines are available, but were not included in the model.

TABLE 16. DRAIN EFFLUENT PREDICTION PROGRAM

Input/Output Option Summary

IOC(I) option I=	Available options		
	Leachate input IOC(4) = 1 or 2	Drain effluent input IOC(4) = 3	Unused options
1	x	x	
2	x	x	
3	x	x	
4	x	x	
5	x	x	
6	x	x	
7	x		
8	x	x	
9	x		
10		x	
11	x	x	
12	x		
13	x	x	
14	x		
15	x		
16	x		
17	x	x	
18		x	
19	x		
20		x	
21		x	
22			x
23			x
24			x
25			x
26			Graphical output options not included in this version of the model.
27			
28			
29			
30			
31			
32			
33			
34			
35			
36			
37			
38			
39			
40			

TABLE 17. DRAIN EFFLUENT PREDICTION PROGRAM

Salt Load Considerations When Drain Effluent Quality is Input (IØC(4) = 3)

Item	Accumulative		Rates*	
	Monthly	Annual	Monthly	Annual
Compute	IØC(5) = 1 or IØC(5) = 2	IØC(5) = 1 or IØC(5) = 2	IØC(5) = 2	IØC(5) = 2
Print	IØC(17) = 1	IØC(18) = 1	IØC(17) = 1*	IØC(18) = 1*
Plot	**	**	**	**

* Rates cannot be output unless computed. Thus, if IØC(5) ≠ 2, the program ignores the IØC(17), IØC(18), and IØC(32) commands to output nonexistent results.

** Plot capability not included in this version of the model, but can be added (see Graphical Output).

I	Value	Option
4	2	The quality of the leachate water is input via magnetic tape from the special ability program EDITCØ - mounted on unit 16, with the format given on Figure 30.
4	3	The quality of the drain effluent is input via magnetic tape from the saturated chemistry program SATCHEM. This tape is mounted on unit 16 with the format as indicated in Figure 29.
	any other value	Quality inputs are not inputed and results will be meaningless.
5	-	In general, this option is used to select the computation of salt load information. The specifics depend on whether quality inputs are for the leachate water or for the drain effluent. The IØC(5) options are now discussed separately for each method of input.

I	Value	Options
5	1	Leachate water quality is input (I0C(4) = 1 or 2). Compute the accumulated salt load (tons/acre) in the drain effluent plus the average discharge rate of salt (tons/acre/year) on an annual basis. The average annual rates for the entire run are also computed. This is done for the individual parameters and the T0TAL L0AD.
5	2	Compute the accumulative salt load (tons/acre) and the average discharge rates of salt (tons/acre/year) for both the leachate water and the drain effluent. The mean annual rate for the entire run is also included. Results are for the individual parameters and the T0TAL L0AD. In addition, if printed results are selected (I0C(17) = 1), mass balance results are included for the aquifer. The initial load in storage (tons/acre) plus the change in storage and the salt remaining in storage (tons/acre) are computed for each year of the study on an accumulative basis. This is done for each parameter and the T0TAL L0AD.
5	any other value	This option is bypassed.
5	-	Drain effluent quality is input (I0C(4) = 3). If a saved tape 8 from a previous run is not being used (I0C(8) ≠ 1), the I0C(10) = 1 option must be included for the run. Logically, both the I0C(8) = 1 and I0C(10) = 1 options should not be used in the same run. If they are, data from tape 8 supercedes that computed by the I0C(10) = 1 option for this run.
5	1	Compute the accumulative salt load in the drain effluent (tons/acre) using monthly data on both a monthly and on an annual basis. Results for the individual parameters as well as the T0TAL L0AD are included. Monthly results are listed if I0C(17) = 1 while annual results are listed

I	Value	Options
		if IØC(18) = 1. Both monthly and annual results are plotted if IØC(30) = 1.*
5	2	Compute the same results as for IØC(5) = 1 and in addition compute the rate of salt load removal in the drain effluent (tons/acre/year) using monthly data on both a monthly and on an annual basis. Results for the individual parameters, as well as the TØTAL LØAD, are included. Monthly results are listed if IØC(17) = 1 while annual results are listed if IØC(18) = 1. Both monthly and annual results are plotted if IØC(32) = 1.*
5	any other value	This option is bypassed.
6	1	Write a saved tape 8 containing the date of the run, title card, parameter name, parameter units code, parameter units label, and the computed concentration for each time and parameter. The data are written in unformated form, with a separate file structure depending on the manner of quality inputs. When the drain effluent quality is input (IØC(4) = 3), the IØC(6) = 1 option is only available when monthly drain discharge data are used (IØC(10) = 1). There are no restrictions when the leachate water quality is input (IØC(4) = 1 or 2). The saved tape 8 may be read in subsequent runs by proper use of the IØC(7) and IØC(8) options when the quality of leachate water is input. When the drain effluent quality is input, tape 8 usage is controlled by the IØC(8) option.
7	-	This option is only available when the leachate water quality is input (IØC(4) = 1 or 2). When the drain effluent quality is input (IØC(4) = 3), this option is bypassed regardless of the value of IØC(7).

---

* When plots are requested, the accumulative results and rates appear on the same graph. Because of the scaling and plotting process, the salt load discharge rates cannot be plotted unless the accumulative salt load is. Consequently, when IØC(5) = 2 and IØC(32) = 1, the accumulative salt load is also plotted even though IØC(30) ≠ 1.

I	Value	Options
		An "equation" or "formula" for the quality of the drain effluent in terms of each change in quality of the leachate water is first developed.* These compositions or results are written on unit 7. Normally unit 7 is a scratch unit. However, when there are many changes, data may overflow the disks requiring that a tape be used. This slows program execution because the unit is rewound for each parameter.
7	1	Use a previously prepared tape 7. However, all data must be read as though this tape were not available, including quality changes. Computations start with the first parameter, the concentration of each being computed with time. The IOC(8) value should be set to zero or left blank in this case.
7	2	Follow the precedure indicated by the IOC(7) = 1 option, except computations do not resume with the first parameter. Instead, computations begin with the parameter following the last one computed and already written on a saved tape 8. The number of the last parameter is given by the value of IOC(8).
7	3	Skip the generation of information on tapes 7 and 8 and go directly to the computation of the salt load results selected by the IOC(5) option. A saved tape 8 (but not tape 7) is required. All inputs, including quality changes, are still required.
7	any other value	Follow the normal computation process starting at the beginning of the problem. Data will be generated and written on unit 7.
8	?	The use of the IOC(8) variable depends on the manner of quality inputs. Where the leachate water quality is input, the IOC(8) value should be set to the number of quality parameters for which results have been written on a saved tape 8. The program reads over the required number of

---

* The present program method is computationally inefficient when the number of leachate water quality changes is large. (See suggested improvements.)

I	Value	Options
		records on tape 8 in preparation to adding new data.* (See IØC(7) option.) If IØC(7) = 0 or 1, 1ØC(8) should be zero or blank. If IØC(7) = 2, then IØC(8) must be set properly. If IØC(7) = any other value, the value of IØC(8) has no effect.
8	1	When the drain effluent quality is input (IØC(4) = 3), a saved tape 8 is to be read. Computations commence with salt load calculations. Thus, the IØC(8) option is logically used only when IØC(5) = 1 or 2. The input deck is then truncated. Tape 8 mush have been created in a previous run by setting IØC(10) = 1 and IØC(6) = 1 when IØC(4) = 3.
8	any other value	This option is not used.
9	-	This option is only available when the leachate water quality is input (IØC(4) = 1 or 2) and salt load computations are requested (IØC(5) = 1 or 2).
9	1	Compute the averrge yearly concentrations of the drain effluent when IØC(5) = 1 or 2 and/or the leachate water when IØC(5) = 2. Results can then be printed using IØC(19) and plotted using the IØC(33) and IØC(34) options.
9	any other value	This option is not used.
10	-	This option is only available when the drain effluent quality is input (IØC(4) = 3).

---

* Note that the 11 format allows only a single-digit number. Therefore, if more than 9 parameters are on tape 8, the program must be modified. (See Limitations and Suggested Improvements.)

I	Value	Options
		Read monthly drain discharge data (card type 21) (i.e., output from drainout program) and compute monthly concentrations. This option is only used when the quality of the drain effluent is input. Additional inputs include card types 18, 19, 20, and 21. Results are computed for each parameter and the TØTAL LØAD. They are listed when IØC(20) = 1, plotted when IØC(26) = 1 and/or IØC(27) = 1, and punched when IØC(21) = 1. Results are placed on a saved tape 8 when IØC(6) = 1.
10	any other value	This option is not used.
11	1	Print travel times as read from card type 5.
12	1	Print the leachate water quality for all changes inputed (IØC(4) = 1 or 2). If IØC(4) = 3, this option is ignored.
13	1	Print the arrival time of each piston displacement front as it reaches the drain for each tube. This is primarily a "debug" print. Only the first 16 fronts are printed. When the drain effluent quality is input (IØC(4) = 3), the word front on output corresponds to slug or the boundary between successive slugs. If there are less than 16 slugs/fronts in the first tube, only NUQUCH are outputed. If there are less than 16 slugs/fronts (or NUQUCH if it is less than 16) for any of the other tubes, printed results may not be meaningful.
14	1	Print the composition of the drain effluent in terms of the various leachate water quality inputs (IØC(4) = 1 or 2) at the time of arrival of each front. This is the information written on unit 7. This is primarily a "debug" print. Only the first 16 terms in the equation are written. This option is not available when IØC(4) = 3.

I	Value	Options
15	1	Print the values in the sorting arrays giving the arrival times, corresponding front, and the corresponding stream tube numbers. This is a "debug" print and has no special headings. This option is available when IØC(4) = 1 or 2, but not for IØC(4) = 3.
16	1	Print the concentration of the drain effluent for each parameter whenever a displacement front reaches the drain. This option is only available when IØC(4) = 1 or 2, but not for IØC(4) = 3.
17	1	Print the load results that are computed by the IØC(5) option when IØC(4) = 1 or 2. When IØC(4) = 3, print the monthly load results that are computed by the IØC(5) option.
18	1	This option is only available when IØC(4) = 3. Print the annual load results that are computed by the IØC(5) option.
19	1	Print the average yearly concentrations selected by the IØC(9) option (i.e., drain effluent if IØC(5) = 1 and drain effluent plus leachate water if IØC(5) = 2). This option is only used when IØC(4) = 1 or 2, but not IØC(4) = 3.
20	1	Print the monthly concentrations for each parameter plus the TØTAL LØAD when IØC(4) = 3 and IØC(10) = 1. This option is not used when IØC(4) = 1 or 2.
21	1	Punch the monthly concentrations for each parameter and the total load as well as the volume of drain discharge. (See Card Output.) This option is only available when IØC(4) = 3 and IØC(10) = 1.
22-25	-	Not presently used.
26-34	-	Graphical output options; necessary subroutines have not been included in this model (see Graphical Output).
35-40	-	Not presently used.

Graphical Output

A graphical output package is available for use with the model but has not been included as part of Volume V. The package can be obtained from the U.S. Bureau of Reclamation, Engineering and Research Center in Denver, Colorado, Code 750.

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APPENDIX

The source code and sample output for the detailed model described in this volume is available on microfische at cost from the authors.

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